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PALEO-OCEANOGRAPHY OF THE MEDITERRANEAN SEA: SOME CONSEQUENCES OF THE WURM GLACIATION

RICHARD S. ANDERSON

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PALEO-OCEANOGRAPHY OF THE MEDITERRANEAN SEA:

SOME CONSEQUENCES OF THE WÜRM GLACIATION

* * * * *

Richard S. Anderson, Jr.

PALEO-OCEANOGRAPHY OF THE MEDITERRANEAN SEA: SOME CONSEQUENCES OF THE WÜRM GLACIATION

by

Richard S. Anderson, Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School

Monterey, California

1965

Thesis
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PALEO-OCEANOGRAPHY OF THE MEDITERRANEAN SEA: SOME CONSEQUENCES OF THE WÜRM GLACIATION

by

Richard S. Anderson, Jr.

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE

from the

United States Naval Postgraduate School

ABSTRACT

The lowering of sea level and altered climatic conditions associated with the Würm Glaciation are examined with a view toward determining their effect on the oceanography of the Mediterranean Sea. Assuming tectonic and other geological alterations to have been negligible, a eustatic sea-level lowering of 450 feet (136 meters) is assumed, and the Würm coastlines of the principal straits and seas are drawn from navigational charts. The effect of the lower sea level on the areas and volumes of the major channels and basins is determined. A quantitative evaluation of the Würm water budget for the Mediterranean Sea is made, and on the basis of this determination, some general conclusions concerning water-mass characteristics and circulations are hypothesized. The water budget is found to have been in a more delicate state of balance during Würm time than at present, whereas the quantity of water exchanged through the Strait of Gibraltar was not drastically altered. Methods of study such as this might prove useful in correlating and substantiating presently existing hypotheses in paleoclimatology, Quaternary geology, paleontology, and paleo-oceanography.

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INTRODUCTION

The purpose of this thesis is to examine some of the oceanographic characteristics of the Mediterranean Sea that prevailed during the last glaciation when sea level was significantly lower and climatic conditions quite different than at present. The European glacial chronology is used herein in view of the subject of the thesis, thus, the last glacial period, which in North America is the Wisconsin, is identified hereafter as the Würm.

The approach taken is to examine the water budget of the Mediterranean Sea, and on the basis of this, to deduce the exchange of North Atlantic and Mediterranean water through the Strait of Gibraltar. From an examination of the water budget, general observations are then made concerning water-mass characteristics and the circulation within the Mediterranean Basin.

An area of study such as this covers a broad array of fields in both their paleo and modern aspects. Climatology, Quaternary geology, and oceanography were all vital to the development of this thesis. The literature in these fields is enormous and the writer could not cover every possible reference. It is felt, however, that a representative cross section of the basic literature was reviewed in the ensuing development.

The hypothesized Würm oceanography rests on numerous presumptions regarding sea level, climatic conditions, and

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oceanographic characteristics, so that the results, while stated quantitatively, represent only reasonble estimates. It was necessary to assume a single sea level and stationary weather and sea conditions during the Würm when, indeed, it is known that sea levels and climatic conditions fluctuated. It was further necessary to assume that present relationships between certain climatic and oceanographic variables existed in a like manner during the Würm time.

GEOGRAPHY OF THE WÜRM MEDITERRANEAN

In order to consider the water masses and circulation of the Würm Mediterranean Sea, it is necessary to examine the geography of this area during the glacial advance. Those aspects of the Würm geography of importance are the location of the Würm shoreline, and the compartmentation of the Mediterranean during the lower sea level.

With regard to location of the Würm shoreline in the Mediterranean, two principal factors should be considered: (1) the glacial lowering of sea level; and (2) tectonic and other geological activity over the interval since the Würm. The effect of the glacial lowering of sea levl was to contract the shorelines, constrict or eliminate water connections between basins, and reduce the surface area of the Mediterranean compared to today. The effect of tectonism has been to alter the positions of coastlines and the size and depth of channels between basins, but, tectonic activity has clearly been of secondary importance compared to the effects produced by sea-level lowering. Other geological events that have altered the margin of the Mediterranean locally are the deposition of deltas and marine sedimentation on the continental shelf.

Tectonism and Other Geological Processes

If sea level in the Mediterranean could be lowered today to the Würm elevation, the new shoreline that would

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result would lie near the outer margin of the continental shelf that encircles the Mediterranean Basin. The new shoreline would not, however, exactly duplicate its location during the Würm because of tectonic changes that have occurred around the margins of the sea and also because of marine sedimentation that has occurred on the shelf since the Würm. The question that is pertinent at this point is: How important were these processes compared with the eustatic sea level lowering of the Würm in determining the location of the Mediterranean shoreline and in determining the configuration and depth of the water connections between basins?

With regard to the location of the shoreline, there are numerous references in the literature to "elevated" and "depressed" shorelines (Zeuner, 1959, p. 276), and there is no doubt that both horizontal and vertical movements have occurred in some coastal areas since the Würm. However, the following considerations indicate that the Würm shoreline would be approximated closely for purposes of this study by a modern contour associated with some given Würm sea-level elevation.

Rates of sea-level change associated with the glacial-interglacial cycles in general during the late Quaternary Period (and probably throughout the Pleistocene), have clearly exceeded vertical tectonic deformation as indicated by the universal existence of the shelf around the Mediterranean

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Basin. Shelves themselves are the product of coastal and nearshore erosion and deposition controlled by the migrating Quaternary shoreline (Thompson, 1961).

In addition, when one considers the short time factor of only about 25,000 years since sea level has risen from the Würm to the present level, a much longer response time would be required for basin-wide uplift or depression of the margins of the sea having the same magnitude as the eustatic change. Nevertheless, tectonic activity has indeed been locally important in various regions throughout the Mediterranean, such as vertical movement in the Bay of Naples (Zeuner, 1950, p. 352).

Horizontal movements around coastal margins are harder to recognize and to evaluate, and little information was found in the literature on the Mediterranean. However, the same arguments presented above regarding the time required for large terrainal movements to take place compared with the short lapse of time since the Würm generally applies to horizontal displacements as well.

In view of the fact that shelves in the Mediterranean (except in the Adriatic Sea and parts of the Aegean Sea) are narrow and the continental slopes are steep, no significant changes can have occurred in the size or shape of the Mediterranean Basin as a result of tectonism.

The effect of sedimentation on the shelves since the Würm has been to add a blanket of marine sediment where the

[illegible]

vigor of water motions has permitted it. This has likewise not significantly altered the position of the Würm shoreline except locally off the delta of the Nile and the few other large rivers, and possibly on the very shallow, nearly flat shelf in the northern Adriatic.

More important to a consideration of the water masses and circulation of the Würm than the shoreline position is the possible post Würm alteration that may have taken place in the waterways which connect basins in the Mediterranean, notably the Strait of Gibraltar, the Strait of Sicily, and the connections with the Black Sea. With regard to the first two, it seems probable that tectonic changes or geological processes of deposition or erosion have not altered those channels significantly during the past 25,000 years. The connection with the Black Sea through the Dardanelles and Bosporus is a more complex and critical situation, and is dealt with later.

In summary, it will be assumed that the location of the Würm shoreline in the Mediterranean is that which would be found if sea level of today's Mediterranean could be lowered to the Würm elevation. It now remains to examine the evidence presented in the literature to ascertain the amount of lowering of sea level during the Würm, in order to determine the shape and area of the Würm Mediterranean.

Eustatic Sea Levels

That sea level during the Quaternary Period was not a fixed datum but rather varied over a large range is an accepted fact. It is also accepted that these fluctuations of sea level were associated with the expansions and contractions of the Pleistocene glaciations. Since the period selected for consideration is the Würm Glaciation, an estimate of the level of the sea occurring during this particular glaciation is of primary interest and is required for water-budget computations. It is also of interest to make some assumptions as to the shape of the curve of rising sea level during the Holocene Epoch. Fortunately, estimates of these former sea level elevations, based on a variety of types of evidence, are fairly numerous in the literature, but they show considerable variability. The elevation of sea level throughout the Würm and Holocene, based on the literature, is depicted in Figures 1 and 2, and is discussed in the sections that follow.

Elevation of the Würm Sea Level

Determination of the elevation of the world oceans during the Würm was complicated by several factors. First, the Würm Glaciation is generally considered to have consisted of two prominent glacial advances separated by a warmer climatic interval, each having a duration of some thousands of years (Flint, 1957, p. 384). Thus, sea level

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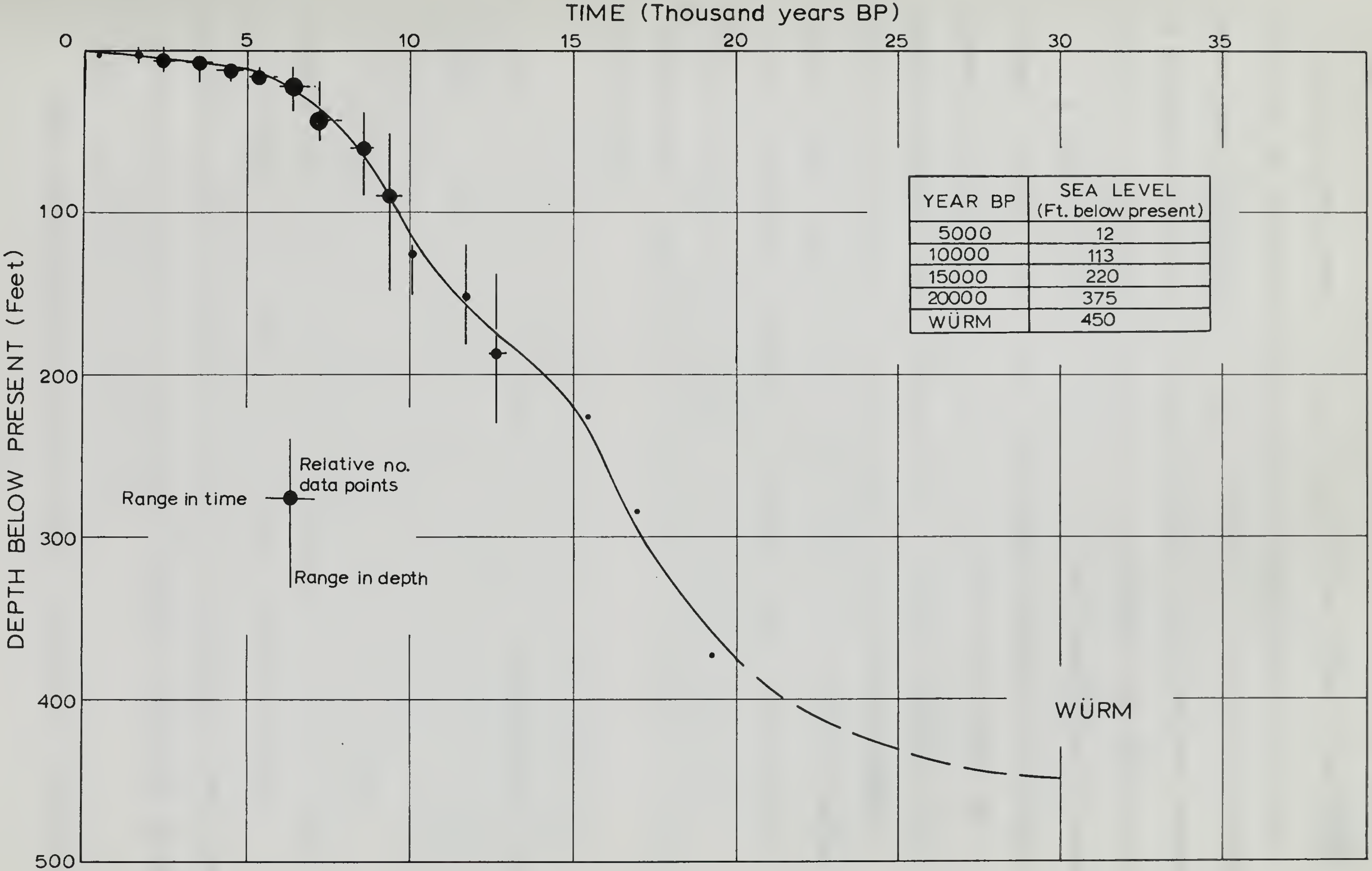
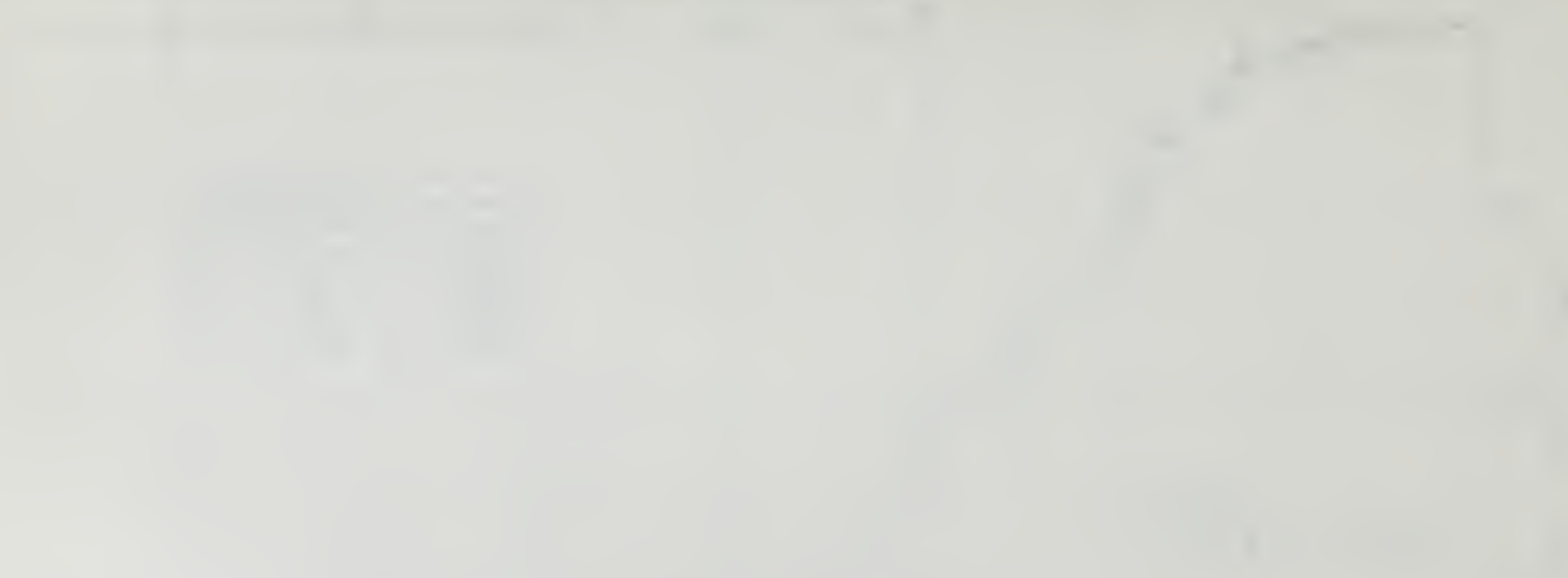
FIG. 1 THE HOLOCENE RISE OF SEA LEVEL (Modified from Shepard,1963)



YEAR BP	SEA LEVEL (Ft. below present)
5000	12
10000	113
15000	220
20000	375
WÜRM	450



probably was not static but fluctuated during the Würm. It is the sea level of the two glacials (Würm II and Würm III) that is of interest here, and it is probable that they were approximately the same over most of the two intervals. A single sea level (discussed below) was therefore assumed, which is considered hereafter to represent the Würm level.

A second factor is that it was not possible, in some cases, to sift out of the literature whether the figures given by an author referred to the Würm sea level, to another glacial sea level, or to a general glacial elevation representative of the entire Pleistocene Epoch. Also, where figures given were identified with the Würm, it was not always possible to relate them to one particular maximum. Accordingly, all reasonable sea-level values were considered in arriving at the Würm sea level used herein.

A survey of the recent literature since 1950 that yielded estimates of glacial sea level is summarized in Table 1. Prior to 1950 the most commonly reported depth of the low stand of sea level below the present was 330 feet or 100 meters (e.g., Blanc, 1937), but more recently papers have been reporting values greater than 330 feet. It is probable that this trend is due to better dating methods, with the advent of the C 14 technique, and to an increasing interest in Quaternary geology. The data in the table are plotted in Figure 2.

For the purposes of this study, a value of 450 feet

TABLE 1. A Summary of Recent Literature on Glacial Sea Levels

Authority	Time of low stand	Depth below present feet	Depth below present meters
Blanc (1937)	post-Tyrrhenian regression (Riss)	330	100
Kuenen (1950)	last advance of land ice (Würm II)	198-264	60-80
	greatest ice advance (during Pleistocene)	295-363	90-110
Zeuner (1950)	pre Flandrian (Würm)	330	100
Fisk & McFarlan (1955)*	maximum lowering during Pleistocene	450	136
Flint (1957)	since last warm inter-glacial time (Würm)	295	90
Russell (1957)	last major low stand about 18,000 years B.P. (Würm II)	450	136
Guilcher (1958)	pre-Flandrian regression (Würm)	330	100
Crary (1960)*	early Wisconsin (Würm I)	378	115
	maximum during Pleistocene	453	137
Novikov (1960)*	early Wisconsin (Würm I)	441	133
	maximum during Pleistocene	525	159
McFarlan (1961): summary	at time of peak of last glacial (Würm II)	450	136
Fairbridge (1961)	Wisconsin (Würm)	330	100
Donn et.al., (1962) summary	Illinoian maximum	450-522	136-159
Shepard (1963) summary	maximum glaciation (during Pleistocene)	360-540	109-165
Eardley (1964)	Wisconsin (Würm)	360-450	109-136

*after Donn, et. al., (1962)

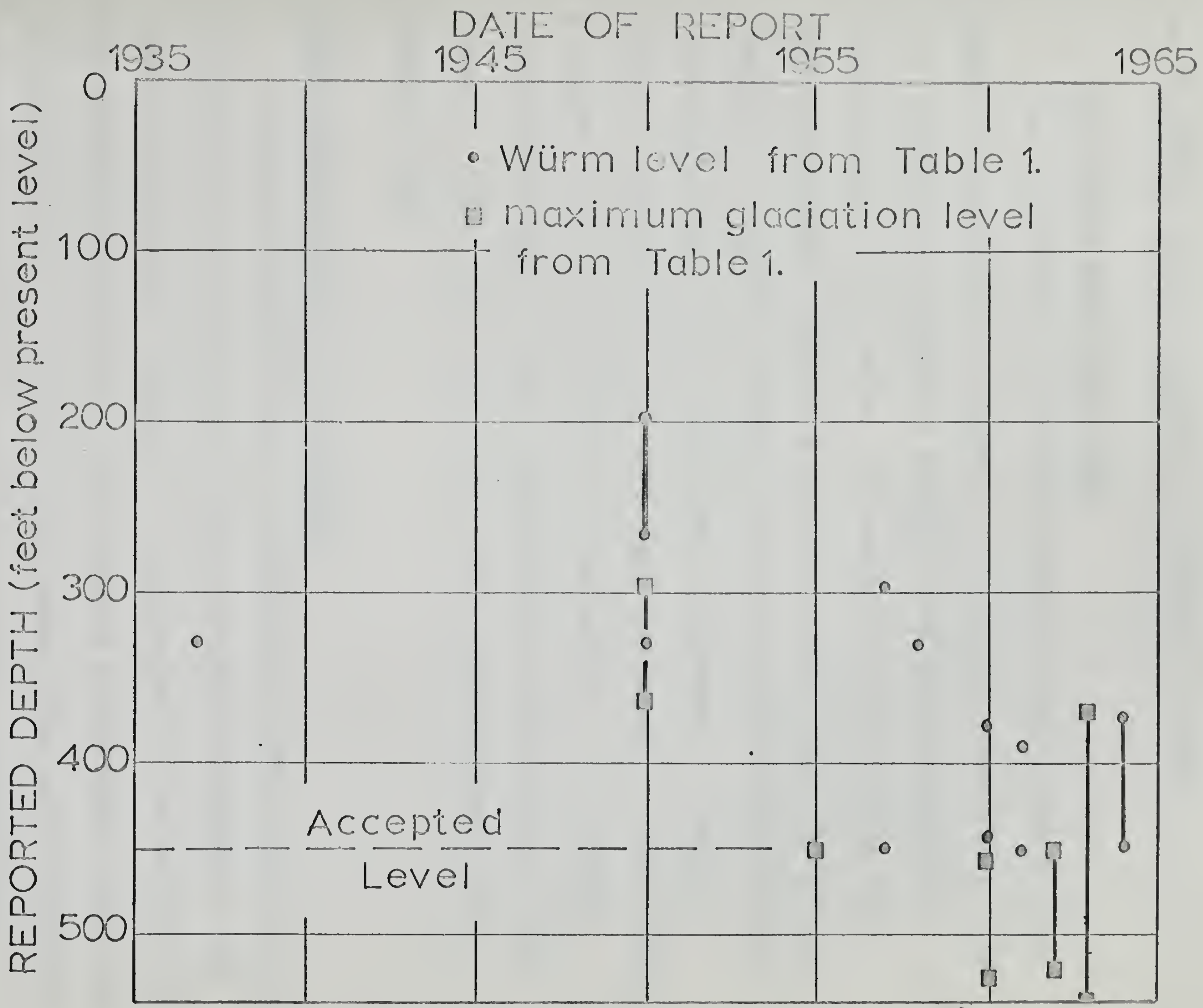


FIG. 2. THE PROGRESSION OF THEORIZED GLACIAL SEA LEVEL

(136 meters) was selected as the Würm level based on Figure 2. This value is in agreement with McFarlan's summary of the literature (1961), and is midway in the 60 to 90 fathom range suggested by Shepard (1963).

Post-Würm Sea-Level Rise

The post-Würm rise of sea level to the present elevation is depicted in Figure 1. The data summarized from the literature by Shepard (1963) have been accepted as the basis for this curve. To arrive at the curve, the writer separated Shepard's data into 1000-year intervals, computed a weighted average of the reported dates and the associated sea levels within each increment (a single date-sea level point per 1000 year increment), then fitted a smooth curve subjectively to the points. No attempt was made to depict small perturbations (Fairbridge, 1961; Curray, 1960) which might have been superimposed on the overall rise.

Wurm Mediterranean Sea Geography

On the assumption that the Würm sea level stood at an elevation of 450 feet (136 meters) below the present, and that no significant changes in the shape of the margins of the Mediterranean basin have occurred since Würm time, the configuration of the Würm Mediterranean Sea was determined by drawing the 450-foot contour on modern navigational charts to represent the Würm shoreline.

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The resulting composite chart, shown in Figure 3, reveals that the general configuration of the Mediterranean Sea during the Würm Glaciation was similar to the present. This is due to the fact that the continental shelves throughout the Mediterranean Sea are, in general, quite narrow, particularly along the southern and eastern shores. Shelf areas of large extent do exist along the coast of Tunisia and southern Sicily, in the Adriatic Sea, and throughout the Aegean Sea. During the Würm, the Tyrrhenian Sea was essentially a gulf, the Adriatic Sea was shrunken to less than half its present area, and the Aegean Sea, equally as modified, had a much constricted entrance. A large river system drained the Black Sea through the Bosporus-Dardanelles channel. Each of the four major basins that form the Mediterranean Sea was even more isolated during this low stand, the channels between basins and into the open Atlantic having all been considerably restricted.

It is worthy of note here to point out the possible archaeological significance of the then exposed islands and mainlands. Shepard (1964) has previously suggested this potentiality in a discussion of the more recent past.

Descriptions of those basins and channels whose configuration most severely influenced the Würm water circulation in the Mediterranean are presented in the discussion that follows. The locations of the Holocene shorelines shown on the accompanying charts are based on the sea level

[illegible]

curve in Figure 1.

Strait of Gibraltar

The Strait of Gibraltar (Figure 4) was greatly elongated and appreciably narrower during the Würm, and represented a very much greater constriction to the exchange of Atlantic and Mediterranean waters than today. The elongation occurred almost entirely on the western end, extending the strait about 25 nautical miles further into the Atlantic Ocean. Several islands appeared in the central region, mostly in the vicinity of The Ridge.

Tyrrhenian Sea

The northern portion of the Tyrrhenian Sea, much of which is continental shelf and continental borderland, was much less extensive during this period (Figure 5). A land bridge from Corsica to Italy was nearly completed, there having been but a narrow passage about 800 feet deep (Table 3) between Cape Corse and Isola Capraia. The island of Elba was a mountain on a peninsula extending out from the present Italian mainland.

In the southern Tyrrhenian Sea (Figure 6), Sicily was joined to Italy by a land bridge across the Strait of Messina. To the west of Sicily, Adventure Bank was above water and extended well into the Strait of Sicily toward North Africa. Sardinia and Corsica were then a single land mass, as the Strait of Bonifacio was closed.

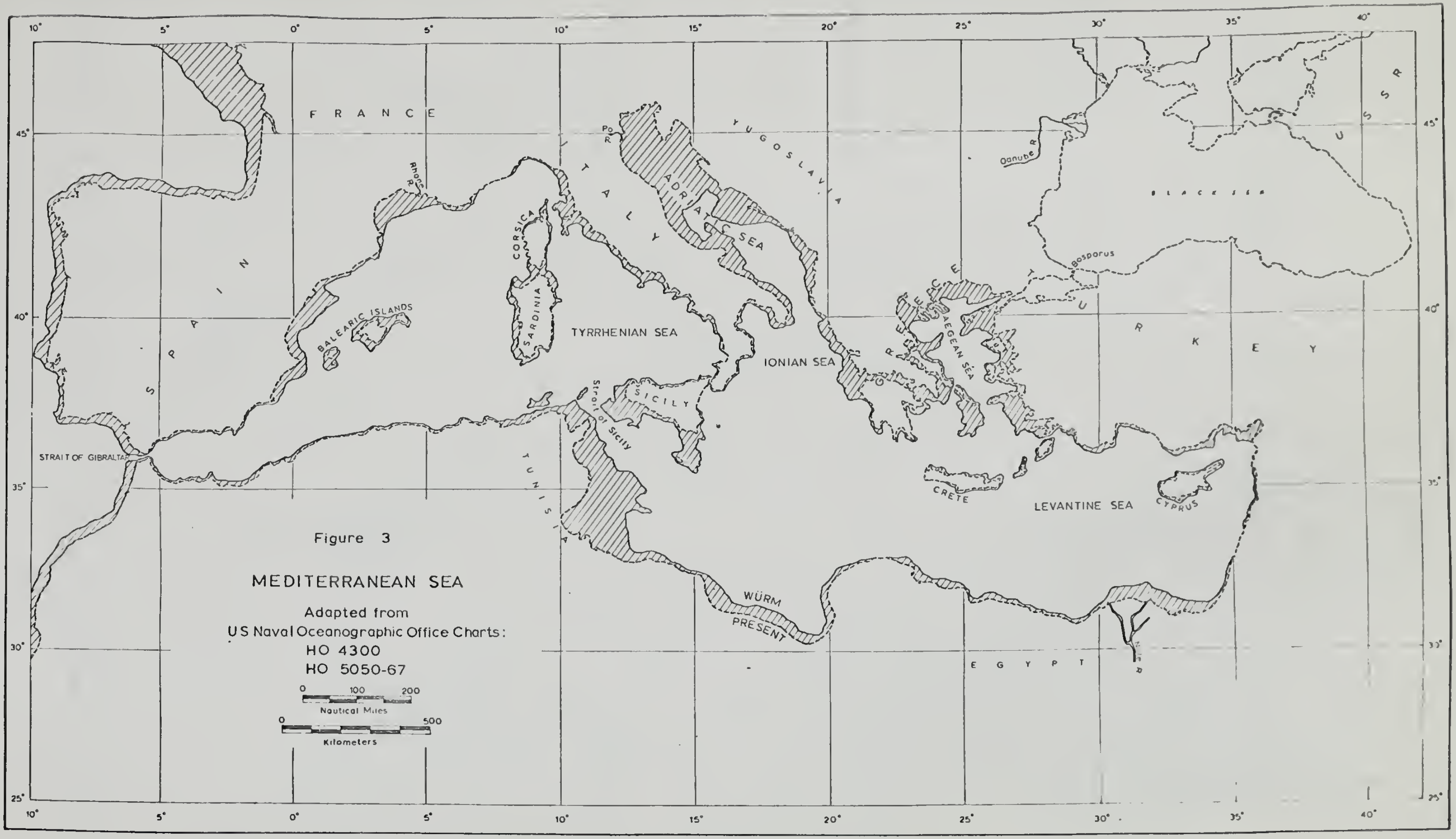

Figure 3

MEDITERRANEAN SEA

Adapted from
US Naval Oceanographic Office Charts:
HO 4300
HO 5050-67

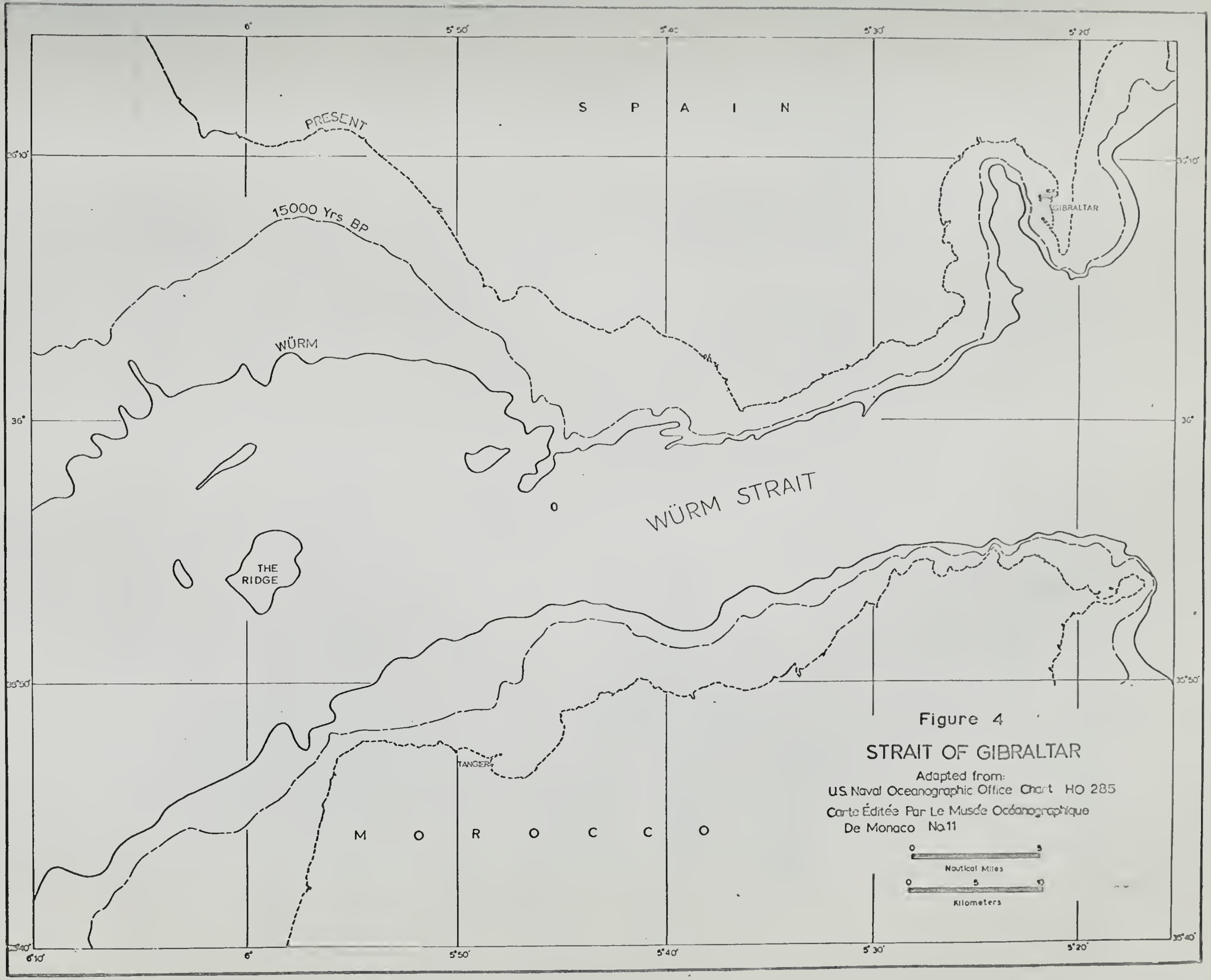

Figure 4

STRAIT OF GIBRALTAR

Adapted from:
U.S. Naval Oceanographic Office Chart HO 285
Carte Éditée Par Le Musée Océanographique
De Monaco No.11

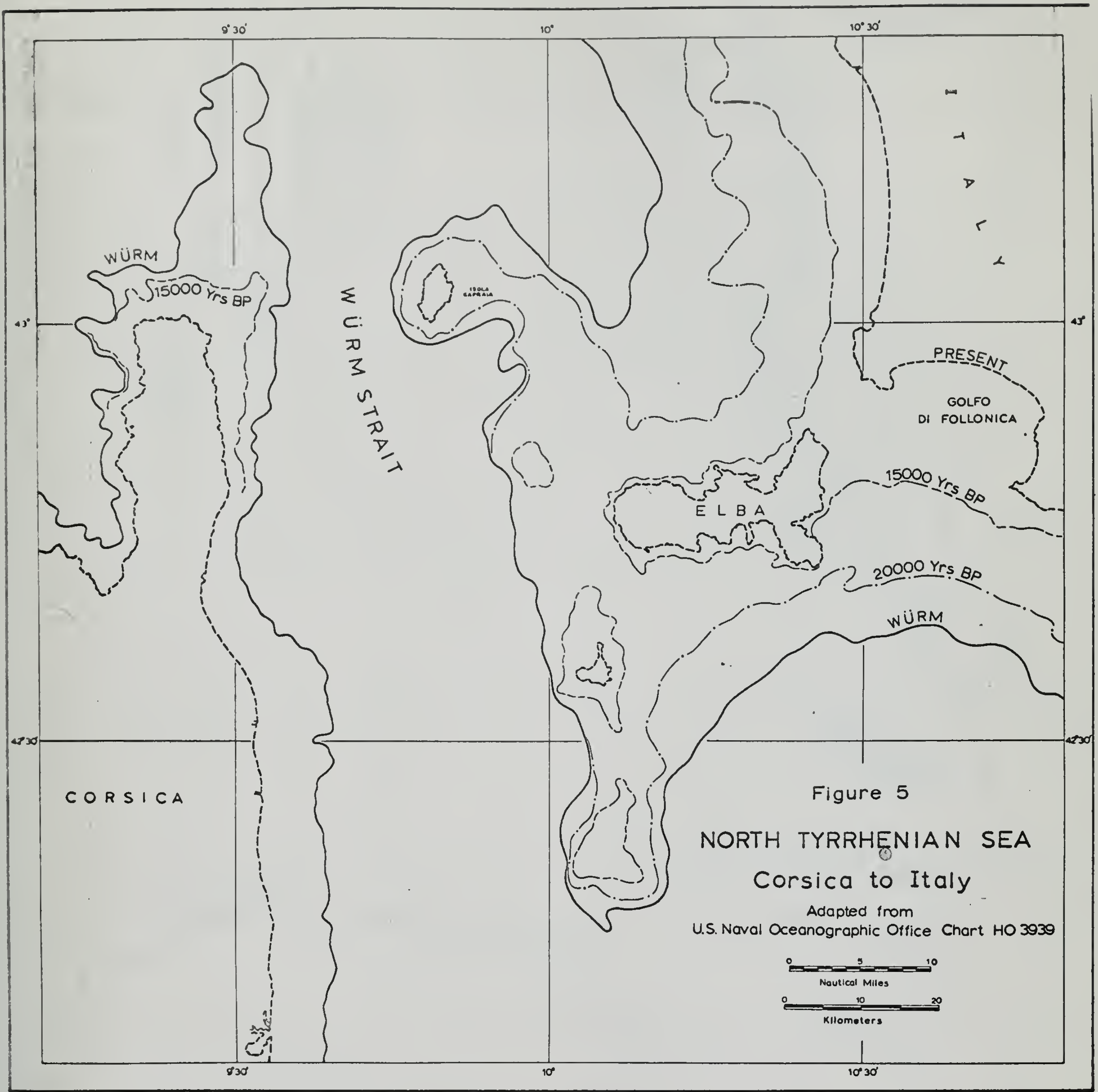

Figure 5

NORTH TYRRHENIAN SEA

Corsica to Italy

Adapted from
U.S. Naval Oceanographic Office Chart HO 3939

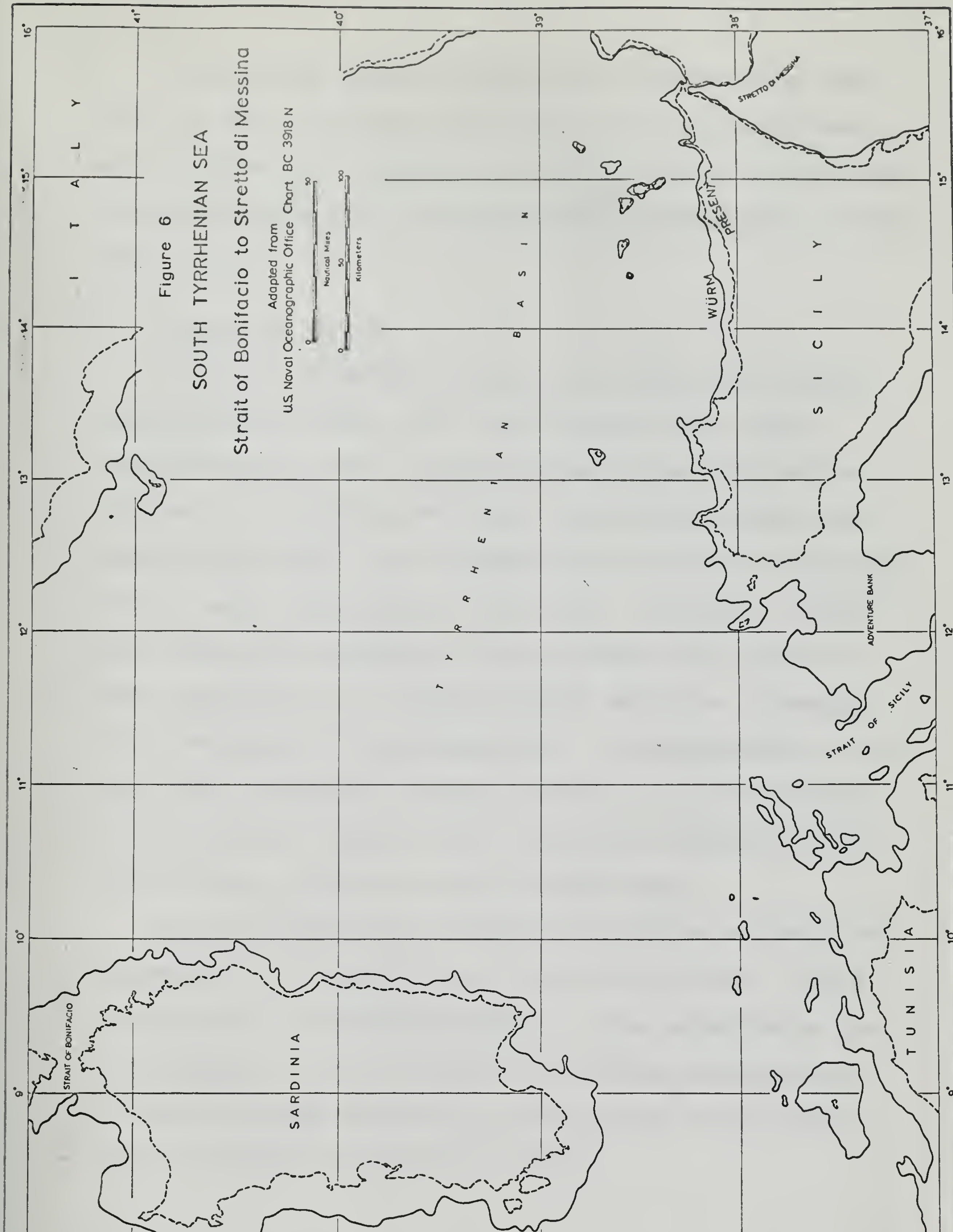
Figure 6
SOUTH TYRRHENIAN SEA
Strait of Bonifacio to Stretto di Messina
Adapted from
U.S. Naval Oceanographic Office Chart BC 3918 N
Nautical Miles
Kilometers
I T A L Y
SARDINIA
S I C I L Y
T U N I S I A
T Y R R H E N I A N B A S I N
STRAIT OF BONIFACIO
STRAIT OF SICILY
ADVENTURE BANK
STRETTO DI MESSINA
WÜRM
PRESENT

The passage between Sardinia and Tunisia being both wide and deep (presently 6600 feet) was little affected, and permitted the only major exchange of water between the Tyrrhenian Basin and the western Mediterranean Basin during this period.

Strait of Sicily

The only connection between the eastern and western Mediterranean in Würm time, this channel was a major constriction to water exchange between these two halves (Figure 7). As mentioned above, the Adventure Bank land mass extended well into the Würm Strait and was responsible for the major difference in this area. Further, a prominent peninsula extending to the northeast from Golfe de Tunis appeared in the present Skerki Bank area, changing the orientation of the channel axis. The appearance of this land mass undoubtedly had some effect on the circulation of the surface currents which flowed (as discussed later) from the west along the North African Coast.

On the southern tip of Sicily the island of Malta was connected to the mainland by a broad land bridge. While this was not a controlling factor in the reduction of the Würm Strait, it did influence the southern entrance and, no doubt, altered somewhat the circulation in the Ionian Sea and through the Strait of Sicily.

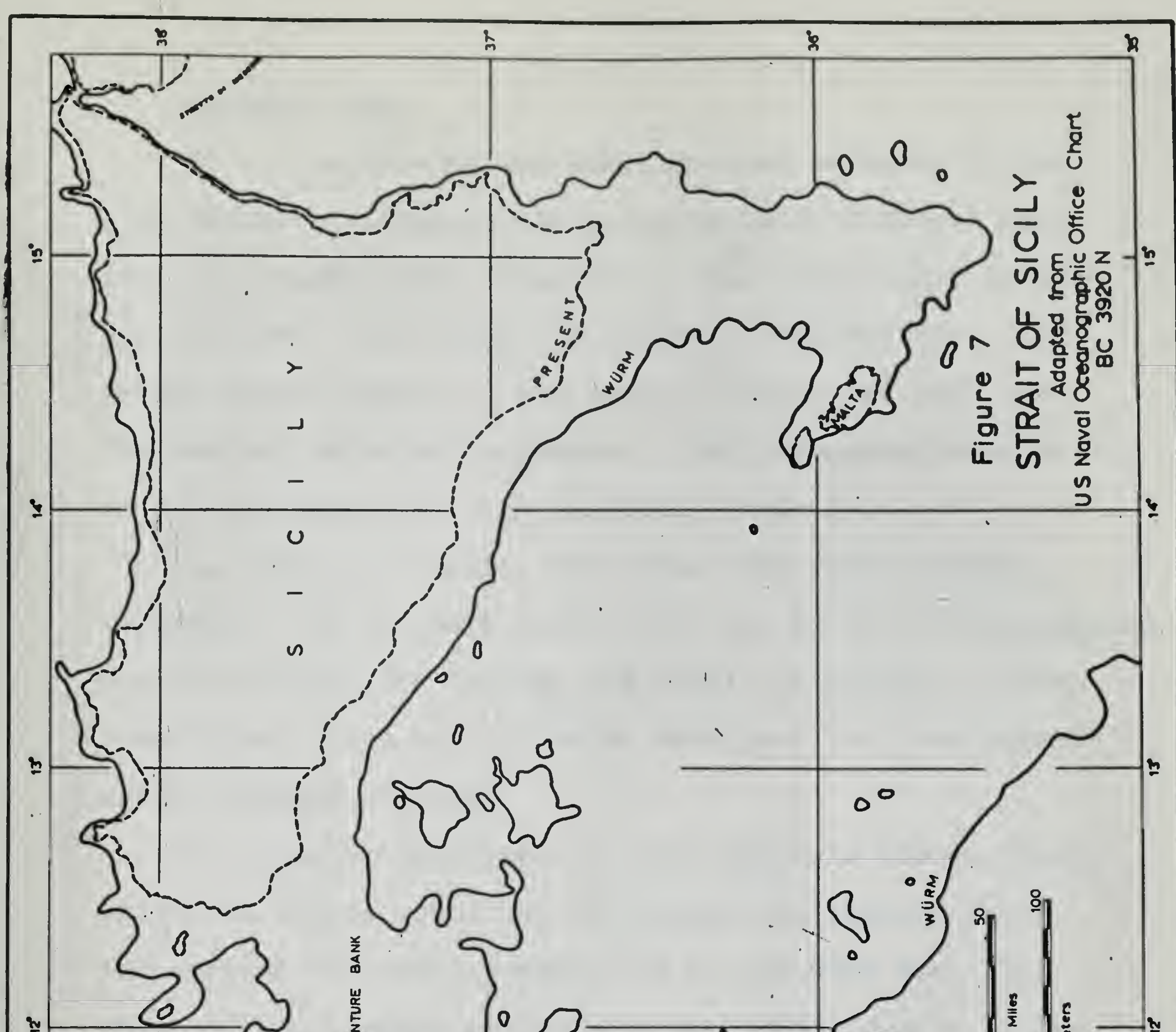

Figure 7
STRAIT OF SICILY
Adapted from
US Naval Oceanographic Office Chart
BC 3920 N

Adriatic Sea

Of all regions in the Mediterranean affected by the Würm Glaciation, the Adriatic Sea probably differed most from its present form (Figure 8). The broad shelf in the northern half was completely exposed, together with the rather broad shelves in the central region off both the Italian and Yugoslavian coasts. The difference amounted to an area reduction of over one half (Table 2).

An impressive basin, more than 6000 feet in depth, existed in the southern half, which was in free communication with the Ionian Sea through the Strait of Otranto. This strait had a deep sill of about 4700 feet, but was considerably reduced in width.

Of primary importance in this region is the Po River, which, no doubt, wound its way across the exposed shelf and emptied into the northern end of the Würm Sea. The shape of the present contours on navigation charts of the northern Adriatic suggests the location of the Po Valley.

Aegean Sea

The Aegean Sea (Figure 9) differs from the simple Adriatic Basin in its complexity of topography in the form of islands, embayments, and basins. The Würm lowering of sea level resulted in an even more isolated water body. Today the connection between the Aegean and the eastern Mediterranean consists of a number of channels. This connection was markedly reduced during the Würm, with the

[illegible]

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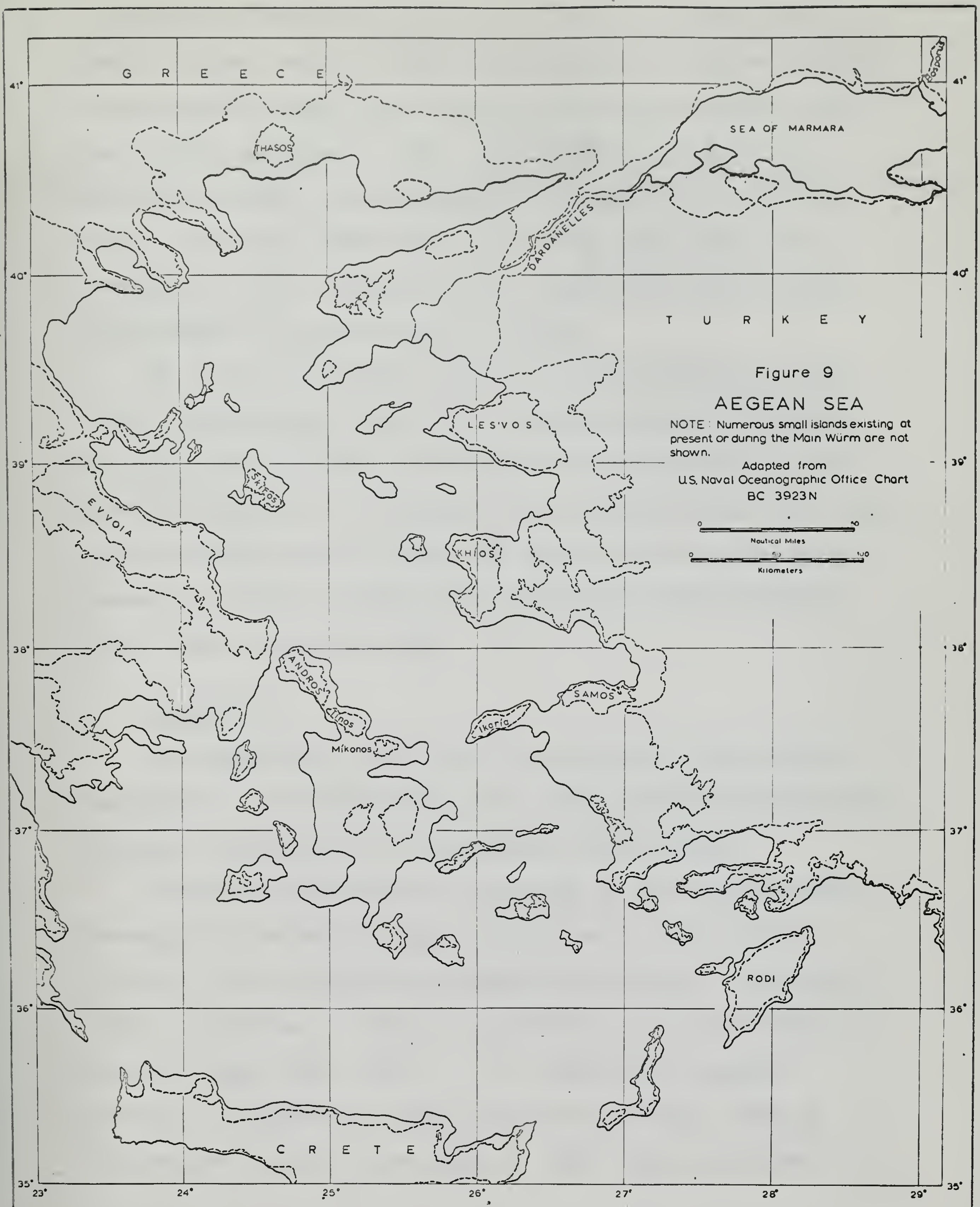
Figure 8
ADRIATIC SEA
Adapted from
U.S. Naval Oceanographic Office Chart
BC 3919 N
0
50
Nautical Miles
0
50
100
Kilometers
PRESENT
10000 YRS BP
15000 YRS BP
WÜRM
WÜRM SEA
YUGOSLAVIA
ITALY
GOLFO DI TARANTO
12°
14°
16°
18°
20°
46°
44°
42°
40°


GREECE
THASOS
SEA OF MARMARA
Bosporus
DARDANELLES
TURKEY
Figure 9
AEGEAN SEA
NOTE: Numerous small islands existing at present or during the Main Würm are not shown.
Adapted from
U.S. Naval Oceanographic Office Chart
BC 3923N
Nautical Miles
Kilometers
LES'VOS
SKIROS
EVVOIA
KHIOS
ANDROS
Tinos
Míkonos
SAMOS
Ikaria
RODI
CRETE
41°
40°
39°
38°
37°
36°
35°
23°
24°
25°
26°
27°
28°
29°

Andros-Tinos-Mikonos island group having then been joined, and, in turn, nearly joining the mainland of Greece, and the Ikaria-Samos island group having been fully connected with the Turkish mainland. Thus, communication existed only through the much reduced passage between Mikonos and the Ikaria Peninsula (Würm sill depth about 1560 feet), and through the small passage between Andros and Evvoia Peninsula (Würm sill depth about 450 feet).

As will be discussed later, the Aegean Sea was apparently the receiving basin for a large river which drained the Black Sea through the Bosporus and Dardanelles. The Würm circulation in the Aegean was presumably such that less saline surface water flowed out through the Mikonos-Ikaria passage into the Levantine Sea, and saline Mediterranean water came in over the sill.

<u>Black Sea</u>

The Black Sea, which must be included in this study because of its intercommunication with the Mediterranean Sea, presents a problem to our geographic description.

Today the Black Sea is connected to the Mediterranean through the Bosporus channel, which has a sill depth of 120 feet, and through the Dardanelles channel, with a sill depth of 210 feet. They are separated by the small Sea of Marmara (depth 4500 feet). If no post-Würm tectonic activity or deposition has altered the channel, then at the assumed eustatic sea level of -450 feet in the Medi-

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terranean, the Black Sea was not in free communication with the Mediterranean Sea. Accordingly, further inquiry into the nature of the connection and its flow is necessary.

Unfortunately, the literature available for this study did not yield many investigations of the Black Sea and its outlet. This does not seem to be a unique problem since several authors note the difficulty in obtaining original literature (Erinc, 1954; Caspers, 1957).

The following items of interest to our development are discussed in the available literature but little common agreement exists on them:

1) Level of the Black Sea:

Zenkevitch (1963) and Erinc (1954) referred to levels somewhat lower than the present which they correlated with the late Pleistocene glacial advances on the basis of geological and biological considerations. The Main Würm Glaciation seems to have been associated with the Novo-Euxine Basin hypothesized by Zenkevitch, or the Post-Uzunlar Basin of Erinc. The limits of these basins, unfortunately, are not clearly defined and this writer was unable to arrive at a suitable level from the information available. From all of the evidence, including that based on salinity, it seems that the Black Sea level was lower during the Würm than at present. On the other hand, Flint (1957, p. 234) postulated a level well above the present on the basis

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of a presumed increased run-off over the amount of evaporation.

2) Salinity of the Black Sea:

In common agreement is the conclusion that a reduction in the salinity below the present low salinity of about 20‰ was associated with the glacial advance. This conclusion is based on faunal evidence, and estimates range from semi-fresh (Zenkevitch, 1963) to brackish (Caspers, 1957).

3) Flow through the Bosporus-Dardanelles:

In greater dispute is the nature of the connection between the Black Sea and the Mediterranean Sea during Würm time. Flint (1957) suggested that a larger outflow occurred through the Bosporus into the Mediterranean on the basis of greatly increased runoff over evaporation. Caspers (1957) proposed that the Black Sea had no outflow due to lowering of its level as a result of reduced runoff, and that the Bosporus was a river valley emptying into it. Erinc (1954) called for outflow through the Bosporus accompanied by great cutting of the channel to depths comparable to the eustatic level of the sea (-450 feet in this case), with subsequent partial refilling due to sedimentation. The latter would permit subsurface inflow of saline water into the Black Sea.

Lowered salinity of the Black Sea during the Würm may

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be explained in two ways. A reduced inflow of saline Mediterranean water could have occurred, but this would have required that the minimum channel depth of the Bosporus be at least as deep as the Würm sea level, as was hypothesized by Erinc. This, in turn, would have required a post-glacial filling or uplift of this channel of at least 330 feet to bring it to its present sill depth of 120 feet. Likewise, the Dardanelles would have required a post-glacial filling or uplift of about 240 feet. The unusual uniformity of the width of the latter river-like channel does not favor this possibility. However, the testing of this hypothesis will have to await further geological field investigation, including sonic probing or coring of the channel.

The other possibility, which is considered more likely here, is that the Black Sea may not have been fully flushed of the salts it had acquired from exchange with the Mediterranean during the high sea level of the Riss-Würm interglacial period (about 75,000 years B.P.; Fairbridge, 1961) just preceding the Würm glacial period. The freshening was very likely accomplished by steady outflow of Black Sea water, diluted by runoff and precipitation in the absence of a saline inflow from the Mediterranean.

The outflow then, if it was not fresh, was at least water of very low salinity, and it is handled as fresh water in our Mediterranean water budget (discussed later). We will thus assume in the following discussions that fresh

[illegible]

water was discharged from the Black Sea through the Bosporus and that no counterflow of Mediterranean water into the Black Sea was present.

A level for the Black Sea cannot be logically deduced in view of the uncertainty regarding the flow through the Bosporus-Dardanelles Channel and the controlling depth therein. Hence, a chart of the sea showing the Würm shoreline has not been included. This is a subject which deserves further investigation.

Basin and Channel Dimensions

The purpose of this discussion is to further emphasize the effect of the lowered sea level on the basins of the Mediterranean Sea and on their interconnecting channels.

As is evident from the foregoing geographic descriptions, some basins experienced quite a drastic reduction in their areas and volumes. A quantitative evaluation of this reduction for several of the basins is presented in Table 2. The Würm data in this table were prepared by the writer using present-day measurements provided by Kossina (1921). It is interesting to note the comparatively small reduction in the western and eastern Mediterranean in contrast to the extreme in the Adriatic Sea.

The pronounced effect that lowered sea level must have had on the circulation of waters between the basins due to reduction of the depths and cross-sectional areas

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TABLE 2. A COMPARISON OF PRESENT AND WÜRM BASIN AREAS ($10^3 km^2$) AND VOLUMES ($10^3 km^3$)

	WESTERN MEDITERRANEAN		EASTERN MEDITERRANEAN (excluding Aegean and Adriatic Seas)		ADRIATIC SEA		AEGEAN SEA		ENTIRE MEDITERRANEAN	
	Area	Vol.	Area	Vol.	Area	Vol.	Area	Vol.	Area	Vol.
PRESENT	821.3	1326	1363.3	2258	132	32	179	104	2495.6	3720.4
WÜRM	735	1220	1213	2183	62	19	148	82	2158	3504
% REDUCTION	10.5	8.0	11.0	3.4	53.0	40.6	17.3	21.1	13.5	5.8

of straits and channels can be visualized from the data presented in Table 3. The table was prepared by the author from measurements taken from navigational charts and other sources. In some cases it was necessary to construct cross-sections from rather scattered soundings, however, these figures are sufficiently accurate for the present discussion. It is rather startling to note that the lowering of sea level must have had a profound influence on nearly all of the major passages. The channel least influenced, the very large passage between Sardinia and Tunisia, was, nevertheless, reduced by quite a significant amount, despite the fact that the passage is deep and wide.

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TABLE 3. A COMPARISON OF PRESENT AND WÜRM CHANNEL SILL DEPTHS AND CROSS SECTIONAL AREAS

	PRESENT SILL (ft)	WÜRM SILL (ft)	PRESENT AREA (km^2)	WÜRM AREA (km^2)	REDUCTION IN AREA (%)
Strait of Bonifacio	180	0	1.5	0.0	100
Strait of Messina	420	0	0.6	0.0	100
Strait of Gibraltar	840	390	2.8	0.8	71
Strait of Sicily	1380	930	21.0	7.1	66
Aegean Sea Entrance	1560	1110	14.0	5.4	62
Cape Corse to Isola Capraia	1260	810	5.5	2.6	53
Sardinia to Tunisia	6600	6150	470000	380000	19

CLIMATOLOGY OF THE WÜRM MEDITERANNEAN

As a necessary prelude to the preparation of a water budget for the Würm Mediterranean, the climatic conditions that prevailed must be established. The following discussion is not a complete description of upper Pleistocene climatic conditions. Such a large undertaking would require more extensive study and is already the subject of numerous papers, including excellent reviews by Wright (1961) and Nairn (1961). The primary purpose here is to define those climatic conditions which had the most profound effect on the water budget of the Mediterranean Sea. When widely divergent hypotheses are encountered, each is briefly discussed. The theories which seem to enjoy the most general acceptance are adopted for purposes of further discussion.

General Circulation

It is commonly agreed that the advance of the glaciers was marked by an equatorial displacement of the westerly wind belt. This would have brought winter cyclones into the Mediterranean region more regularly than today. Details on the circulation are presented by Willett (1950) and Wright (1961). Willett has prepared a mean pattern of the general circulation during the northern-hemisphere winter of the Würm ice maximum. This pattern is based in part on anomalous pressure patterns presently prevailing during winters of severe storms (Wright, 1961). A portion of

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Willett's pattern is shown in Figure 10. From the figure we note several features of particular interest:

1. In northeastern Europe the glacial anticyclone, a dynamic high-pressure system, indicates a high frequency of blocking action which must have shunted the westerly winds into the low latitudes.

2. The low-pressure area in the North Atlantic is an extension or eastern cell of a Polar cyclonic center of cyclogenesis located in the general region of Iceland.

3. A center of cyclogenesis occurred in the east central region of the Mediterranean Sea and resulted in the pluvial conditions which numerous investigators have reported for North Africa, the Near East, and Western Asia (Brooks, 1949; Flint, 1957).

According to Willett, migratory low-pressure centers, moving out of the North Atlantic Cyclonic System, tended to move primarily in two directions, each being controlled by the blocking action of the high-pressure system centered over the Scandinavian ice sheet (Figure 11). Those moving to the north around the blocking high skirted the west and north sides of the ice sheet. Those moving to the southeastward, entered the Mediterranean Basin and regenerated in the region of the Ionian Sea. It is these lower latitude storm tracks which were no doubt responsible for producing a pluvial climate. From the Mediterranean center of cyclogenesis, storms probably travelled northeastward

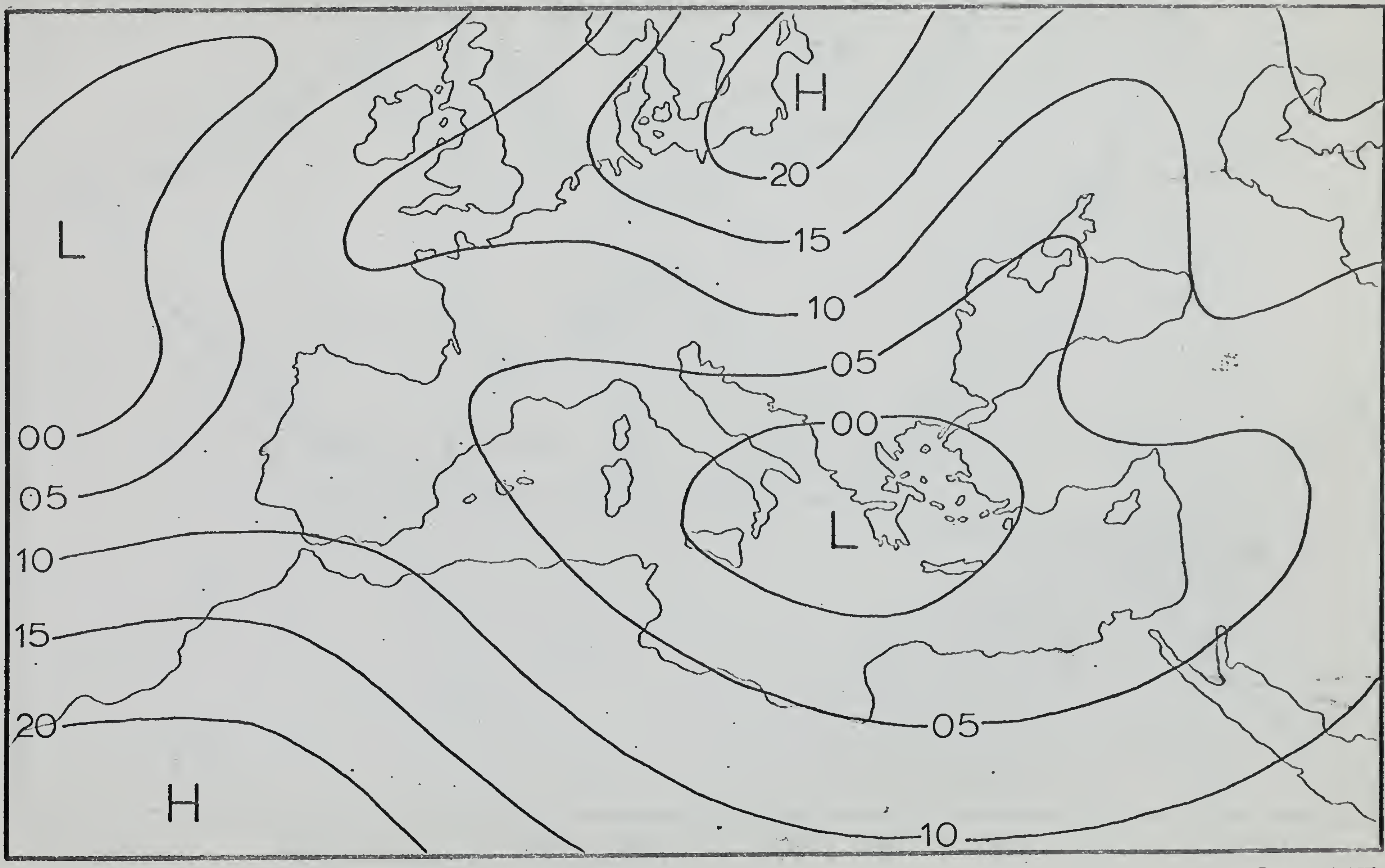

Figure 10. GENERAL CIRCULATION OF THE WINTER SEASON DURING THE WÜRM ICE MAXIMUM (after Willett, 1950)

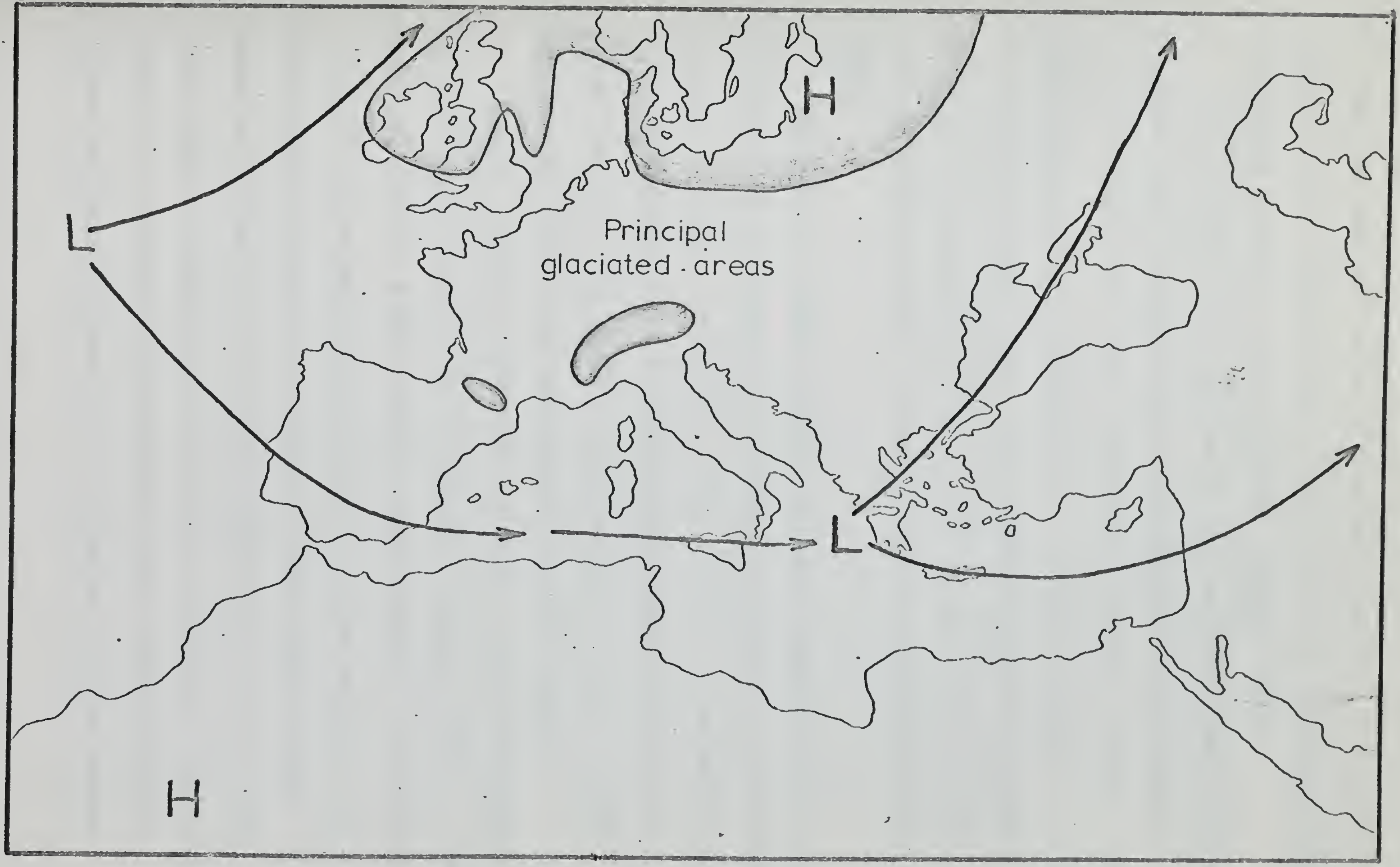

Figure 11. PRINCIPAL STORM TRACKS OF THE WÜRM ICE MAXIMUM (after Willett, 1950)

to feed the eastern side of the Scandinavian ice sheet and eastward into Central Asia to maintain the extreme pluvial conditions reported for that area (Flint, 1957).

In the upper atmosphere we can expect a large number of upper-level troughs and a significant displacement of the jet stream into lower latitudes (Willett, 1950). These conditions further substantiate a pluvial climate. It is of interest to note here that pluvial conditions appear to have been characteristic of all of the present arid and semi-arid areas of the earth during the Würm (Flint, 1957).

During the summer season, Willett suggests that the southerly storm tracks were shifted poleward to the edge of the ice sheet. We would, thus, expect a reduction of storm activity in the Mediterranean region during the summer season, but still not comparable to the present dry summers which are experienced in this region.

Poser, using a different approach, has constructed two circulation patterns for Europe (Wright, 1961). One pattern, for the Würm glacial summer season, is based on climatic and vegetational provinces. The second, for a late-glacial phase of the Würm in the summer season, is based on morphology of ancient sand dunes. The former bears some resemblance to Willett's pattern for the winter season, but several differences appear when Willett's winter pattern (Figure 10) is adjusted for the summer

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season. Poser's latter pattern shows an extensive high-pressure ridge extending over most of Europe and the eastern Mediterranean, with closed high-pressure centers over central Europe and Spain. Since this pattern is for a late phase of the Würm Glaciation, such configuration cannot be directly compared with Willett's pattern.

Air Temperature

It is widely accepted that general temperature reductions were experienced during the glacial advance (Lamb, 1961, after Flohn; Zeuner, 1959, p. 254). Estimates of the temperature reduction have been made and are based on geological and paleobiological evidence and on snow-line depressions. The magnitude of the reduction cited is generally at least 4C (Wright, 1961).

Isothermal charts of Würm temperatures have been derived for Europe for the months of January and July by Klute (1951). Portions of these are reproduced in Figures 12 and 13. The dashed lines indicate additions by the author and are merely continuations of Klute's isotherms across water bodies.

Klute's January pattern, when compared to the present temperature distribution, shows a greater temperature reduction than 4C. If such a distribution did not actually exist, there is little doubt that the extreme northern portions of the Mediterranean Sea and the entire Black Sea were covered by ice during the winter season. This

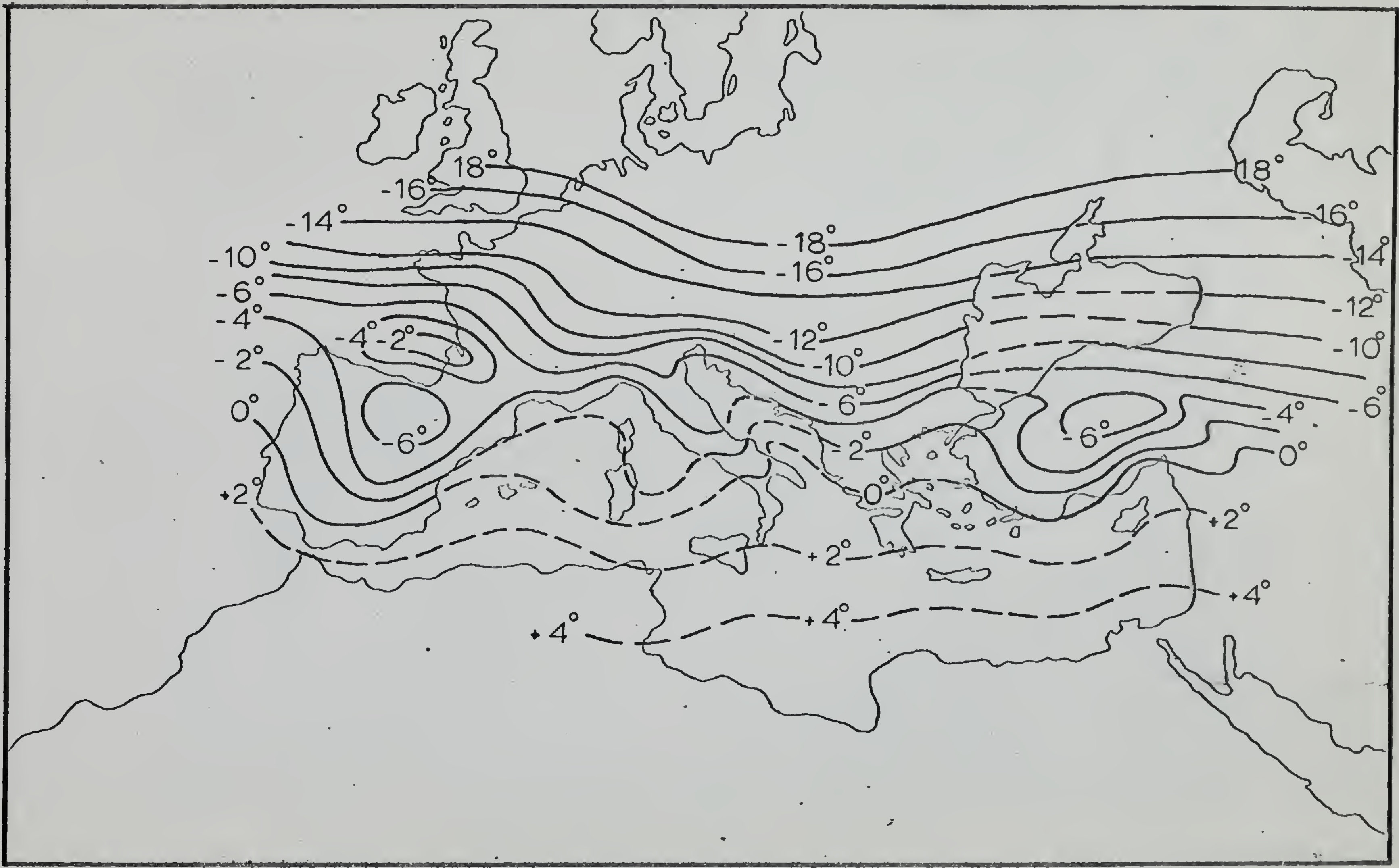

Figure 12 WINTER (JANUARY) AIR TEMPERATURE DISTRIBUTION DURING THE WÜRM ICE MAXIMUM (·modified from Klute, 1951)

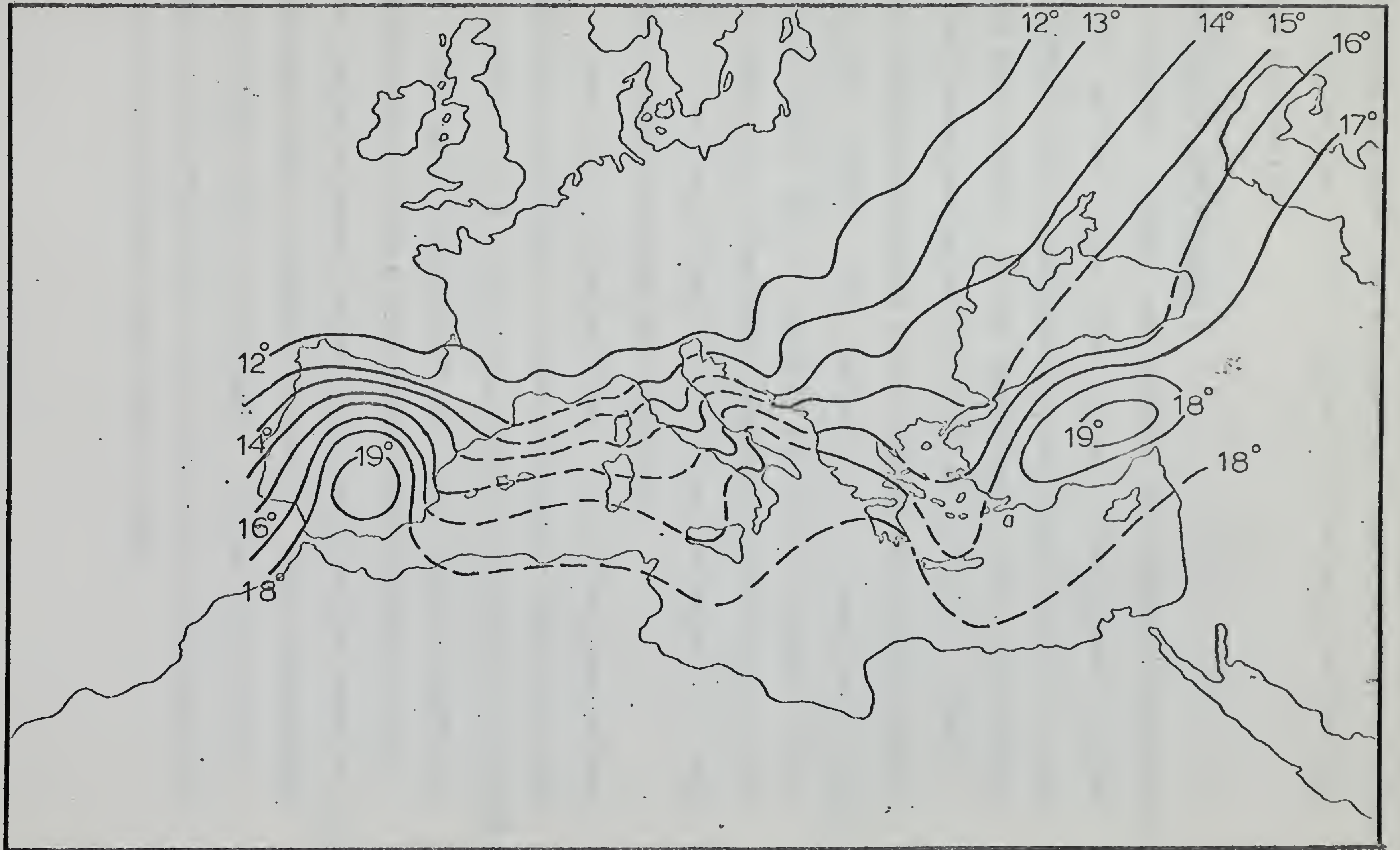

Figure 13. SUMMER (JULY) AIR TEMPERATURE DISTRIBUTION DURING THE WÜRM ICE MAXIMUM (modified from Klute, 1951)

obviously affected the evaporation from these water bodies. The implications of this factor will be more evident in later discussion.

Sea-Surface Temperature

Emiliani (1955a) has derived sea-surface temperatures of past geologic ages from ratios of the oxygen isotopes in certain marine planktonic Foraminifera found in cores. Using this method, he has determined, from a core sample in the Levantine Basin (33° 54'N and 28° 29'E), that a sea-surface temperature of 8C existed during this period (Emiliani, 1955b). This compares with present-day temperatures of about 16C in February and 26C in August. From this same core, a seasonal temperature variation in the basin of between 6C and 11C has been determined for this period, which compares with 10C today.

Klute (1957) also provides us with four sea-surface temperature estimates. These values are shown encircled in Figures 14 and 15 and from them the author has attempted the rather gross analysis of the sea-surface temperature distributions for the winter and summer seasons during this glacial advance, based principally on the trend of the isotherms shown in Figures 12 and 13. This presentation is included solely for interest. Further calculations dealing with evaporation will employ only the temperature at the four locations specified by Klute.

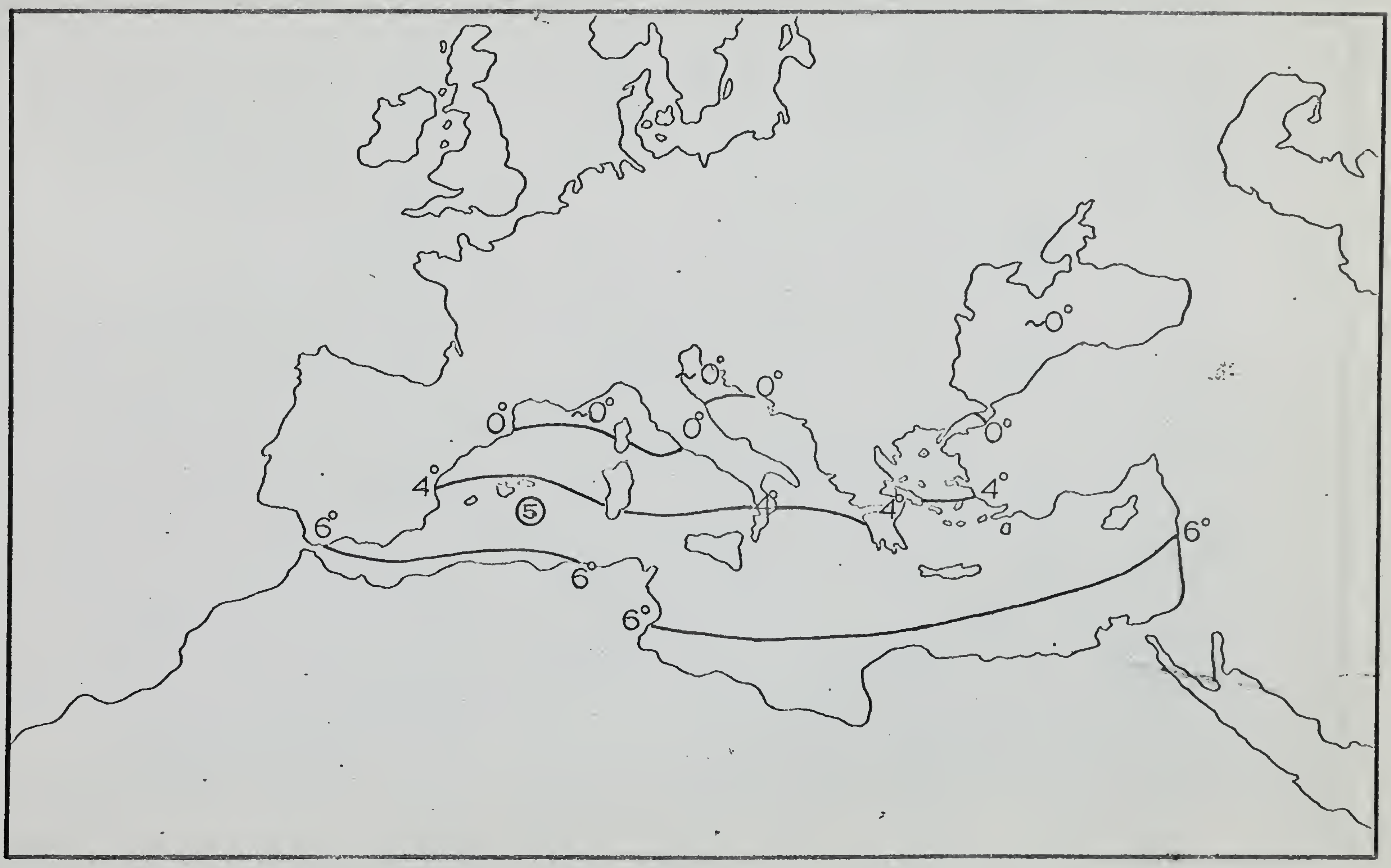

Figure 14. WINTER (FEBRUARY) SEA SURFACE TEMPERATURE DISTRIBUTION DURING THE WÜRM ICE MAXIMUM

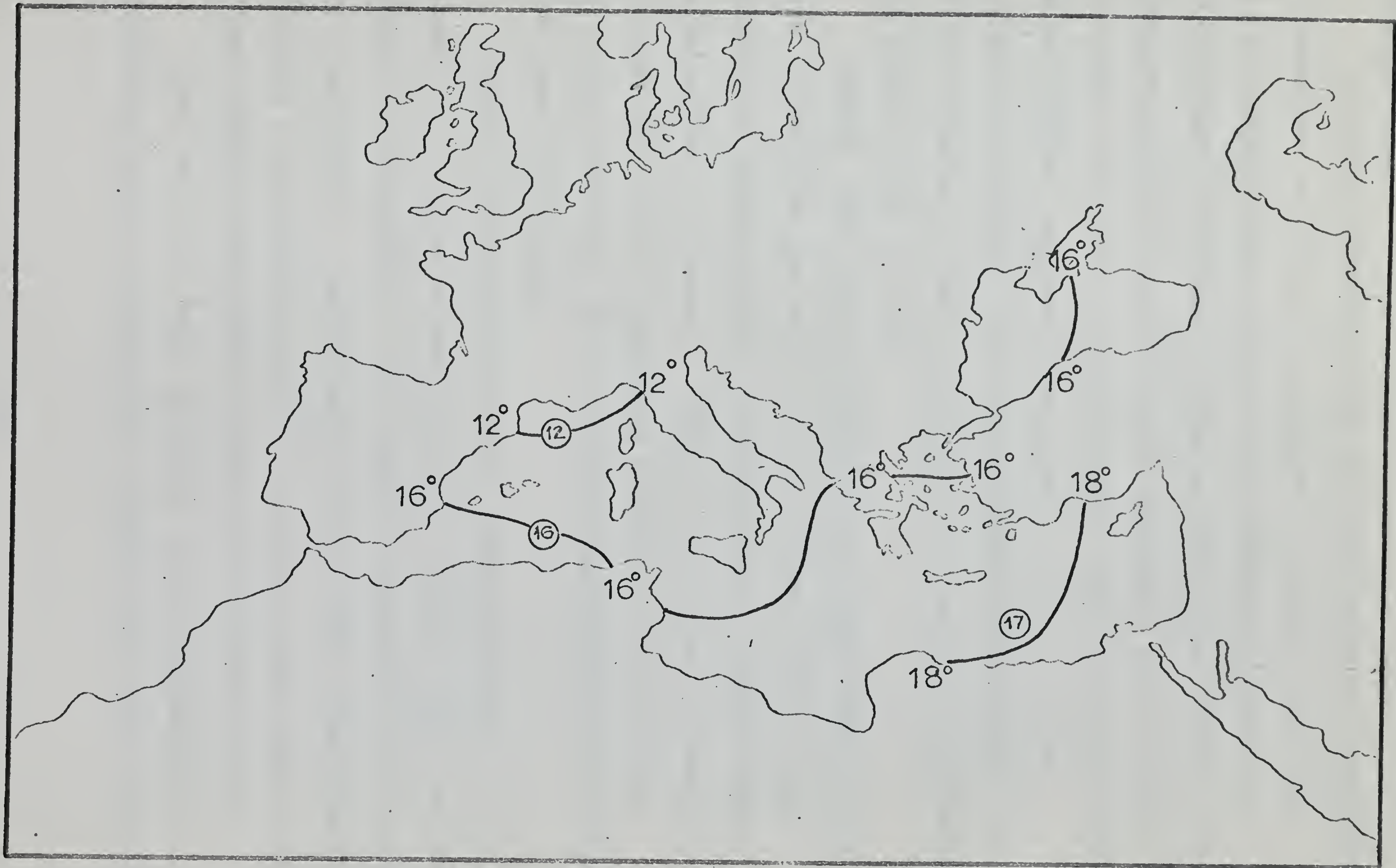

Figure 15. SUMMER (AUGUST) SEA SURFACE TEMPERATURE DISTRIBUTION DURING THE WÜRM ICE MAXIMUM

Precipitation

It follows directly from our discussion of the general circulation and from the evidence of pluvial conditions in the Mediterranean region that a general increase in precipitation must have existed at that time. It not only appears probable that the storms migrating into the Mediterranean Basin and the cyclogenesis occurring there would have produced increased precipitation, it is further reasonable to assume that the increased precipitation was distributed more evenly throughout the year, as hypothesized by Brooks (1949, p. 276).

Brooks (1949, after Flicker) also states that at the time of maximum glaciation of the northwest Pamir Range, located in Central Asia, rainfall was four to five times greater than at present. Although this area is somewhat removed from that of immediate interest to us, it does give some indication as to possible magnitudes which might have been experienced.

Not all investigators are in common agreement on the question of increased precipitation. Wright (1961) reviews several investigations which report a decrease in the amount of precipitation. Additionally, Klute (1957, after Klein) presents a precipitation chart of Europe, which shows reductions ranging between 20% and 80% of the present amount.

Thus, we find a wide variation in the estimated precipitation amounts ranging from somewhat less than presently

[illegible]

exists to four or five times greater. This subject certainly merits further investigation; however, for the purposes of this paper we will assume that a general increase in precipitation was most likely for this period. A mean precipitation for the Würm will be assumed later in the discussion on the water budget.

Wind Velocity

The wind velocity is of particular interest here because it is one of the controlling factors of the rate of evaporation from the underlying surface.

The previous discussion regarding intensified storm activity over the Mediterranean in Würm time leads to the conclusion that wind speeds were probably higher during this glaciation than at present, since higher wind speeds are ordinarily associated with storm activity. Also, inherently related to storminess are large atmospheric pressure gradients. In Figure 16 is shown an overlay of the January mean pressure pattern from present climatic data (Meteorological Office, 1962), on Willett's pattern of Figure 10 for the winter season. Accepting Willett's pattern, it is quite obvious that higher gradients did, indeed, exist during the glacial advance.

Quantitative estimates of wind speed were not discovered in the literature. However, the wind field can be derived from the pressure pattern by application of the geostrophic relationship, as follows:

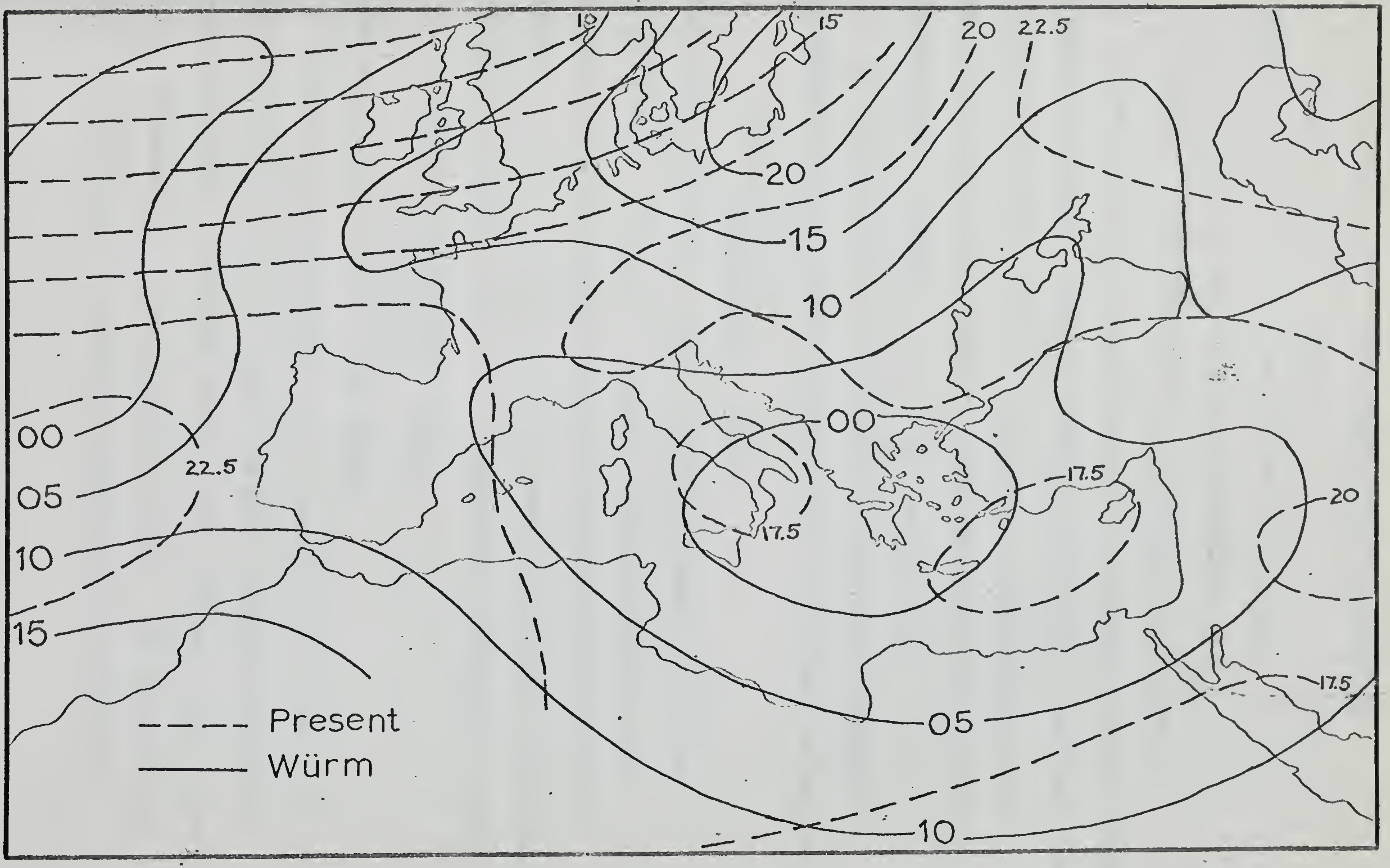

Figure 16. PRESENT AND WÜRM WINTER PRESSURE PATTERNS

The geostrophic wind speed, W_g, is given by

$$W_g = (\alpha/f)\ (\Delta p/\Delta n)$$

where: α is the specific volume of air

f is the Coriolis parameter

$\Delta p/\Delta n$ is the horizontal pressure gradient.

After deriving a geostrophic wind speed from the surface pressure gradient over the Mediterranean Sea, the wind speed at the sea surface can be computed by application of an empirical conversion factor. This procedure can be easily circumvented, however, in the following way:

By assuming that the specific volume and Coriolis parameter have remained constant since the Würm, we may write:

$$(W_g)_w = \frac{(\Delta p/\Delta n)_w}{(\Delta p/\Delta n)_p} (W_g)_p ,$$

where the subscripts p and w denote present and Würm, respectively. If we now further assume that the ratio between the geostrophic wind and the surface wind, which depends on the stability of the lower atmosphere, has also remained constant, which is a reasonable assumption, then:

$$(W_s)_w = \frac{(\Delta p/\Delta n)_w}{(\Delta p/\Delta n)_p} (W_s)_p$$

where W_s is the surface wind speed.

From this relationship it is possible to obtain the sea surface wind speed during the Würm from the pressure gradients shown in Figure 16 and from surface winds shown in any present-day climatological atlas. The sea-surface wind direction can be inferred directly from Willett's

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pressure pattern using an empirical direction factor that is in standard use in meteorology (U.S. Navy Hydrographic Office, 1951).

Figure 17 has been developed in this manner and depicts the mean surface wind field derived for the Würm winter. The present wind speeds were obtained from mean monthly values for coastal stations given by the Meteorological Office of the Air Ministry of Great Britain (1962).

The surface wind over the Mediterranean does not directly enter into the water budget discussed in the next section, but is used to evaluate the evaporation from the Mediterranean during the Würm.

Evaporation

No quantitative estimates of evaporation amount during the Würm were discovered in the literature. However, based on the foregoing discussions, some qualitative observations can be made concerning this part of our climatological description.

Evaporation loss from the sea surface, according to classical theory, is directly proportional to the air-sea temperature difference and to the surface wind speed. In middle latitudes during the summer season the air temperature is nearly equal to the sea-surface temperature, hence, evaporation is small. During the winter season in most regions of the oceans, the air temperature is greatly lowered while the water temperature does not experience a large

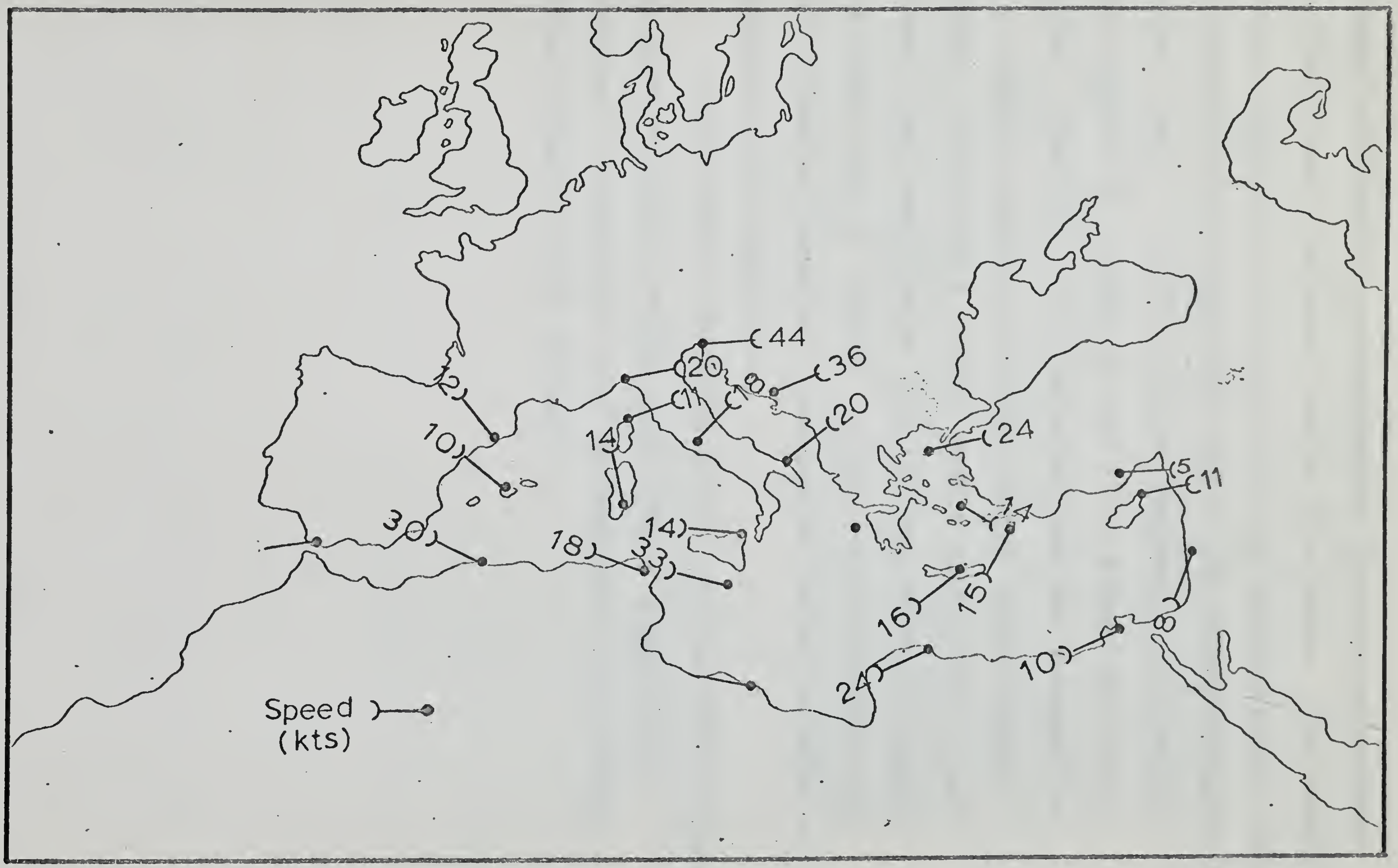

Figure 17. WINTER SURFACE WIND FIELD OF THE MEDITERRANEAN REGION DURING THE WÜRM ICE MAXIMUM

change; accordingly, the evaporation from the sea surface is significantly increased during this season. The average air-sea temperature difference over the Mediterranean today is about 1C in the summer and -2C in the winter (Meteorology Office, 1962). The Würm air-sea temperature difference, from Figures 12 through 15, was 2C in summer and -4C in winter. Therefore, it is expected that the evaporation was somewhat greater in the Würm winter season than at present. With regard to the surface wind speed, it has already been demonstrated that the mean Würm wind speed was higher than at present, so that the wind factor must have caused an increase in evaporation during the Würm as compared to the present day.

It thus appears that evaporation from the Mediterranean was greater during the Würm than today. Quantitative estimates of evaporation will be presented in the water-budget discussion that follows.

THE WÜRM WATER BUDGET

We have now completed a general description of the Würm climate and can proceed with a determination of the water budget.

<u>The Water-Budget Equation</u>

We will assume that the water level of the Mediterranean Sea remained constant during the Würm. This required that the amount of water gained from all sources must have equalled the amount lost over a given interval of time. This may be expressed by the water-budget equation for stationary conditions:

$$A_i + B_i + R + P = A_o + B_o + E \qquad (1)$$

where A_i is amount of Atlantic water flowing into the Mediterranean through the Strait of Gibraltar

A_o is amount of Mediterranean water flowing out to the Atlantic Ocean through the Strait of Gibraltar

B_i is amount of water flowing into the Mediterranean from the Black Sea

B_o is amount of water into the Black Sea from the Mediterranean

P is precipitation

R is run-off

E is evaporation

In the following discussion, the subscripts w and p will denote Würm and present conditions, as in the previous section.

Let us now examine each of the terms of equation (1) quantitatively and attempt to assign values to them.

Evaporation

Several empirical relations exist in the literature for determination of the amount of evaporation from the surface of the sea (Laevastu, 1960; Sverdrup, 1942). These relations have basically the same form, and express evaporation as a function of wind speed and the water-vapor gradient in the air immediately above the water. In general form, these relationships may be expressed as:

$$E = k_1 (e_s - e_a) W_s \qquad (2)$$

where E is the mean annual evaporation amount (cm/yr)

e_s is the average saturated water-vapor pressure of the air at the sea surface as determined from the sea-surface temperature (mb)

e_a is the average water-vapor pressure of the air at a height of 6 m (mb)

W_s is the average surface wind speed (m/sec)

k_1 is an empirically determined constant.

Sverdrup (1942) has given k_1 a value of 3.7 for wind speeds between 4 and 12 m/sec. We may thus write:

$$E = 3.7 (e_s - e_a) W_s \qquad (3)$$

We will consider that this equation was valid during the Würm glaciation.

An examination of equation (3) reveals that we have

previously determined most of the parameters necessary to evaluate the evaporation during the Würm. It only remains to make some estimation of the relative humidity which generally existed during that time, in order to compute e_a. To do this, let us assume that the Würm relative humidity approximated the present mean relative humidity during the winter months (November through March). From climatic data for several shore stations around the Mediterranean Sea, we arrive at a relative humidity of 70% (Meteorology Office, 1964). The relative humidity at the sea surface can be considered to be 100% since e_s is a saturation vapor pressure.

Using the air and sea surface temperature distributions in Figures 12 through 15 for the four ocean stations shown, the following table was constructed in which the vapor-pressure values were obtained from a standard vapor pressure diagram for air.

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TABLE 4.

Average Water-Vapor Gradient in the Air above the Water ($e_s - e_a$)

Station	Season	T_s	T_a	e_s	e_a	$e_s - e_a$
1	wi	5	1	8.8	4.5	4.3
2	su	12	13	14.0	10.5	3.5
3	su	16	17	18.2	13.6	4.6
4	su	17	18	19.3	14.5	4.8
					Sum	17.2
		Average annual ($e_s - e_a$):				4.3 mb

Ordinarily over ocean areas most of the annual evaporation is accounted for in the winter season, largely because the air-sea temperature difference is greatest then. It is interesting to note from the table that the temperature difference is, indeed, greater in winter, but the temperatures are so much lower in that season that the larger temperature difference is not reflected in a larger vapor-pressure difference. It appears, then, that most of the seasonal difference in evaporation can be attributed to the seasonal variation in the wind.

We have previously proposed a mean wind-speed pattern for the winter season (Figure 17). Assuming this to be representative, an average annual surface wind speed of 20 knots (10 m/sec) has been accepted.

Inserting the appropriate values into equation (3),

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]					[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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we obtain an evaporation rate of 159 cm/yr, which compares with a present evaporation rate of 145 cm/yr for this region. Multiplication of this Würm evaporation rate by the surface area of the Würm Mediterranean Sea (Table 2) gives a mean evaporation loss of 109,000 m^3/sec.

In these calculations we have disregarded any reduction of evaporation amount due to ice formation in the northern regions of the Mediterranean during the winter season.

<u>Precipitation</u>

As discussed earlier, a general increase in precipitation during the Würm seems to be a valid assumption. Quantitative determinations for such an increase were not discovered in the literature, hence, for use in balancing the water budget we will arbitrarily assume an increase of twice the present amount. From Sverdrup's data (1942, p. 648), the present annual precipitation for the Mediterranean is 41 cm/yr, so that we will use a value of 82 cm/yr. This gives an average precipitation amount of 56,200 m^3/sec over the area of the Würm sea.

<u>Run-off</u>

We are now faced with the task of estimating the run-off into the Mediterranean Sea during the glacial advance. Since water exchange with the Black Sea is treated separately, run-off into the Black Sea is not included here.

Run-off from the land is a function of many factors

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including the form and amounts of precipitation, air temperature, evaporation, etc., and it is not within the province of this paper to attempt to arrive at a run-off figure on the basis of water-budget considerations over the land.

In addition, no estimates of run-off were encountered in the literature. The run-off assumed herein for the Würm was taken to be equal to twice the present run-off of 7,300 m^3/sec, as given by Sverdrup (1942, p. 648). This assumption was arrived at on the basis of the following considerations.

The existance of pluvial conditions in the Würm required an increase in run-off and precipitation over evaporation throughout the river basins draining into the Mediterranean. However, it should be noted that both precipitation and run-off (P + R) and evaporation (E) could be lower than today and yet allow a pluvial climate to develop. If evaporation over the basins was higher than at present, as was concluded earlier for the Mediterranean Sea, then, indeed, run-off and precipitation had to be higher than at present. In general, an increase in precipitaion usually means an increase in run-off. Another factor favoring increased run-off is the increased supply of melt water derived from the margins of the expanded glacial ice caps that blanketed the mountain masses of southern Europe.

We will thus use in the following discussion a run-off

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quantity of 14,600 m^3/sec.

Exchange with the Black Sea

Inflow to the Black Sea

As assumed earlier, there was no intrusion of Mediterranean water into the Black Sea during this period. Hence, this term of the water budget equation is 0.

Outflow from the Black Sea

In order to make an estimate of this quantity, we must attempt a calculation of the water budget for the Black Sea. Let us again assume the level of this sea remained constant during the Würm, and that the sea was nearly fresh according to our earlier discussion. We can then write as a water budget equation:

$$P_B + R_B = E_B + B_1 \qquad (4)$$

where P_B is precipitation into the Black Sea

R_B is the run-off into the Black Sea

E_B is evaporation from the Black Sea

B_1 is as previously defined: the flow out of the Black Sea into the Mediterranean.

Let us make the same assumptions concerning the run-off and precipitation as we did for the Mediterranean Sea, i.e., twice the present. Thus, using a value of 7,600 m^3/sec for the present precipitation and 10,400 m^3/sec for the present run-off (Sverdrup, 1942, p. 650), the Würm values were:

$$P_B = 15,200 \text{ m}^3/\text{sec}$$

and $$R_B = 20,800 \text{ m}^3/\text{sec}.$$

The fact that the surface area of the Black Sea during the Würm was different from that of today was not taken into account in arriving at these values.

The evaporation amount could not be handled in the same manner as with the Mediterranean, since no sea-temperature data were available. An estimate was made by considering the Black Sea region to be completely frozen in winter. As shown in Figure 12, the entire sea lies well north of the OC isotherm in winter and, although the water body might not have been completely frozen, a large portion of it must have been ice covered. Accordingly, no significant evaporation could have occurred for a period of, perhaps, three months. Hence, evaporation was reduced to 75% of the present evaporation. Using a value given by Sverdrup (1942, p. 650) for today of 11,500 m^3/sec, the Würm value was then:

$$E_B = 8,600 \text{ m}^3/\text{sec}.$$

Substituting the values obtained above into equation (4) we obtain a value of the outflow of Black Sea water into the Mediterranean of:

$$B_i = 27,400 \text{ m}^3/\text{sec}.$$

The Black Sea water budget is summarized in Table 5.

TABLE 5.

Summary of Water-Budget Terms for the Würm Black Sea

	Precipitation (m^3/sec)	Run-off (m^3/sec)	Evaporation (m^3/sec)	Würm Outflow (m^3/sec)
Present	7,600	10,400	11,500	12,600
Würm	15,200	20,800	8,600	27,400

It can be noted from the table that run-off, precipitation, and evaporation in the Black Sea are of about the same magnitude so that a change of any one would result in a significant difference in the discharge into the Mediterranean, assuming the level of the Black Sea remained constant.

Exchange with the Atlantic Ocean

Under stationary conditions, the amount of salt contained within the Mediterranean Basin must remain constant during the period of discussion. Accordingly, the amount of salt carried into the Mediterranean through the Gibraltar Strait must have equaled the amount carried out. In the first approximation, this can be expressed by (Sverdrup, 1942, p. 147):

$$S_i \; A_i = S_o \; A_o \tag{5}$$

where S_i is average salinity of the incoming Atlantic water, and, S_o is average salinity of the outgoing Mediterranean water.

Combining this with the water balance equation (1) for the Mediterranean, we can write:

$$A_i = D \; \frac{S_o}{S_o - S_i} \tag{6}$$

$$A_o = D \frac{Si}{S_o - Si} \tag{7}$$

where D is the evaporation surplus or deficit, $E-(B_i + P + R)$.

In order to solve these equations, the average salinities had to be calculated. This was accomplished as follows. Let us first consider that the total salt content of the world oceans was the same in Würm time as it is today. By taking the difference in volume between the Würm and present oceans into account, we can compute the average increase in salinity of the Würm ocean over the present ocean from the following relationship:

$$S_w V_w = S_p V_p \tag{8}$$

where V is the volume of the world oceans. But $V_w = V_p - \Delta V$, where ΔV is that volume removed from the oceans with the lowering of sea level. Equation (8) thus reduces to:

$$S_w = \frac{V_p}{(V_p - \Delta V)} S_p \tag{9}$$

Kossina (1921) gives the volume of the present oceans as:

$$V_p = 1{,}370{,}323 \times 10^3 \text{ km}^3.$$

Using Kossina's data on the distribution of area versus depth for the world oceans, we obtain for a sea-level lowering of 136 meters:

$$\Delta V = 47{,}968 \times 10^3 \text{ km}^3.$$

Equation (9) may then be written:

$$S_w \doteq 1.036 S_p. \tag{10}$$

[illegible]

Thus, the average salinity of the Würm ocean was 3.6% higher than that of the present oceans.

We will assume that the dynamics of the North Atlantic circulation, and its relationship to the other oceans, was basically the same in Würm time as today so that the salinity of the surface water was increased proportionately. Therefore, this equation can be used to obtain a value for the salinity of the inflowing Atlantic water during the Würm, given the present salinity. We will use 36.25 o/oo, given by Sverdrup (1942, p. 647), for the present salinity of the inflowing Atlantic water through the Strait of Gibraltar. Accordingly, the Atlantic inflow during the Würm had a salinity of:

$$S_i = 37.55 \text{ o/oo}.$$

We must now estimate the salinity of the Mediterranean water flowing out through the Strait of Gibraltar into the Atlantic Ocean. Defant (1961, p. 164) developed an empirical relation for the open oceans, $S_s = S_d + k_2$ (E-P), which explains the surface salinity, S_s, as resulting from a balance between water exchange with the atmosphere (E-P) and mixing below with a large reservoir of water of constant salinity, S_d. This may be written:

$$k_2 = \frac{S_s - S_d}{E - P} = \frac{\text{vertical mixing}}{\text{atmospheric exchange}} \qquad (11)$$

We will consider that this same relationship applies to the Mediterranean Sea, with the modification that (E-P)

[illegible]

is replaced by $E-(P+R+B_1)$ since the effects of run-off and the Black Sea contribution also affect the salinity. We will also assume that the ratio was the same during the Würm as at present. We can then write:

$$\frac{(S_s - S_d)_w}{(S_s - S_d)_p} = \frac{[E-(P+R+B_1)]_w}{[E-(P+R+B_1)]_p} . \qquad (12)$$

If we further consider that the salinity of the inflowing and outflowing water through the Strait of Gibraltar bears some fixed relationship to the vertical salinity distribution in the surface layers of the Mediterranean, and that this relationship was the same during the Würm as at present, we can write:

$$\frac{(S_i - S_o)_p}{(S_s - S_d)_p} = \frac{(S_i - S_o)_w}{(S_s - S_d)_w} \qquad (13)$$

Combining equations (12) and (13) gives:

$$\frac{(S_i - S_o)_w}{(S_i - S_o)_p} = \frac{[E-(P+R+B_1)]_w}{[E-(P+R+B_1)]_p} . \qquad (14)$$

Using the values previously established we solve equation (14) for the salinity of the Mediterranean water flowing out over the Gibraltar sill into the Atlantic to obtain:

$S_o = 37.92$ o/oo

We are now able to solve equations (6) and (7) for the quantity of flow through the Strait of Gibraltar, whereby,

we obtain:

$$A_i = 1{,}101{,}600 \text{ m}^3/\text{sec.}$$

$$A_o = 1{,}090{,}800 \text{ m}^3/\text{sec.}$$

<u>Summary</u>

The component parts of the water budget are summarized in Table 6. The reduction in surface area of the Mediterranean resulting from the lower sea level is accounted for in all unit conversions by using Würm surface area presented in Table 2.

It appears that all processes operating during the glacial maximum acted to reduce the net flow through the Strait of Gibraltar (A_i-A_o) compared with today. Table 6 reveals the delicate balance of the Würm water budget under the conditions hypothesized. An evaporation surplus, E-(P+R+B_i), on the order of only 10,800 m^3/sec, appears to have existed during Würm time as opposed to the present evaporation surplus of 70,000 m^3/sec. This pronounced reduction did not, however, appreciably alter, percentagewise, the rate of exchange of Atlantic and Mediterranean water through the Strait of Gibraltar.

It is quite obvious that with a small additional increase in precipitation and run-off over evaporation, an evaporation deficit would have existed. This subsequently would have resulted in a reversal of the flow through the Strait of Gibraltar and possible stagnation of the deep and

TABLE 6. MEDITERRANEAN SEA WATER BUDGET: PRESENT AND WÜRM

	GAIN (m^3/sec)				LOSS (m^3/sec)		
	INFLOW FROM ATLANTIC	INFLOW FROM BLACK SEA	PRECIPITATION	RUN-OFF	OUTFLOW TO ATLANTIC	OUTFLOW TO BLACK SEA	EVAPORATION
PRESENT	1,750,000	12,600	31,600	7,300	1,680,000	6,100	115,400
WÜRM	1,101,600	27,400	56,200	14,600	1,090,800	0	109,000

bottom waters, as is the case in the Black Sea today. If such a condition existed in the Würm Glaciation, evidence should be preserved in the bottom sediments of the Mediterranean and revealed in core samples. No such reports were found in the literature examined, hence, we may reasonably assume that the flow was not reversed. In this respect, the hypothesized water budget probably gives a true representation. However, due to the many variables and the number of assumptions inherent in the calculations, it is impossible to evaluate each quantity accurately. It is felt, though, that the trend of each quantity is in the correct direction, so that the water budget provides a realistic order of magnitude approximation to the actual conditions that existed during the Würm.

WATER MASSES AND CIRCULATION

Now that we have examined quantitatively the water budget for the Würm Mediterranean Sea, we are able to make some deductions regarding the water masses and the circulation.

Due to the many assumptions and generalities involved in the earlier discussions, it is not feasible to attempt a detailed description of the various water masses. There probably existed portions of the water column comparable to the present day intermediate water and transition layers. We will, however, consider only two broad divisions; the water which formed the surface layers, and the deep water filling the basins.

The surface water of the Atlantic Ocean entering the Gibraltar Strait had a salinity of about 37.5 o/oo and temperature of greater than 6C. This water flowed in at an estimated rate of 1,101,600 m^3/sec. If we assume that the current occupied one half of the cross-sectional area of the strait, then the current velocity was about 80 cm/sec (1.6 knots). The present average velocity is 34 cm/sec (Defant, 1961).

After passing through the strait, the surface water no doubt followed its present course along the northern coast of Africa, as shown in Figure 17. A portion of the flow was diverted northward along the west coast of Corsica-

[illegible]

Sardinia and another portion passed into the Tyrrhenian Sea.

This surface water, the salinity of which was increased somewhat by evaporation, was then cooled in the northern regions during the winter season, and sank, to form the denser deep and bottom waters. The deep water, with a salinity of about 37.9 and temperature of near OC, then passed out into the Atlantic over the sill at the Strait of Gibraltar. Thus, the deep and bottom water appears to have been formed by the same processes and in the same general localities as at present. The localities were probably of greater extent, caused by more extensive and intensive cooling. The amount of deep and bottom water produced might accordingly have been greater and consequently, a more rapid renewal of the basin water may have occurred. We might also expect the deep and bottom water to have had a higher oxygen content than at present.

The circulation within the eastern Mediterranean Sea may have been quite different than we presently observe. The surface water must have had a relatively low density due to increased precipitation and to the great quantity of fresh water from the Nile, Po, and other rivers, and from the Black Sea, and also due to the generally higher surface temperatures than in the western basin (Figure 13). This light water probably flowed out of the eastern basin

at the surface through the Strait of Sicily, with inflow of more saline water over the sill from the western basin. Renewal of basin water by winter cooling to produce the deep and bottom water, probably occurred at a rate sufficient to prevent stagnation within the basin.

Figure 17 summarizes the average annual surface circulation presumed for the Würm. It must be emphasized that this pattern is based on the many assumptions and observations discussed earlier. In order to further substantiate the current pattern, other factors must be investigated. Core samples would be of particular benefit for such a study. On the other hand, the present investigation might help in the analysis of bottom sediment samples and in their correlation with the Würm Glaciation as reflected in the water masses and circulation of the Mediterranean Sea.

Figure 18. WÜRM SURFACE WATER CIRCULATION WITHIN THE MEDITERRANEAN SEA

CONCLUSIONS AND ACKNOWLEDGMENTS

When one commences a study such as this he is likely to be overwhelmed by the vast amount of varied literature on the subject. Perhaps this factor limits the value of the investigation, but perhaps it is just this factor which gives added impetus to such an undertaking because of the necessity of making order out of the variety of viewpoints presented in the literature.

If one takes various postulated conditions, supposedly of general occurrence sometime in geologic past, and attempts to make a quantitative evaluation of any kind for some particular region of the earth, certain factors may reveal themselves as being completely unreasonable, or at least highly unlikely. On the other hand, such quantitative analysis might serve to confirm a given set of postulated conditions.

In this study, no hypotheses were confirmed or destroyed. Nevertheless, the Mediterranean Sea is a particularly apt test area since, being controlled by the narrow passage at Gibraltar, changes within or around the basis should produce quite decided consequences readily detectable by field observation. For example, core analysis may reveal periods of stagnation or of marked freshening of the basin water.

No doubt, each of the authorities cited would take issue with portions of this work, since parts were accepted from many authors but all was accepted from none. The conditions prevailing during the Würm that were accepted were those deemed most reasonable from the available literature.

This field of inquiry developed from a number of discussions with Professor W. C. Thompson of the Department of Meteorology and Oceanography, to whom the author is further indebted for his assistance and encouragement during all phases of development of the thesis. I should also like to express my thanks to Commander R. W. Haupt, USN, of the Department of Meteorology and Oceanography, for aid in the selection and procurement of charts, and to Professor G. R. Luckett, Director of Libraries, and his staff of able assistants for their cooperation in obtaining many of the necessary publications and papers referenced herein.

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